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Influence of fuel injection system faults of marine diesel engine on the heat release characteristics

Abstract: The paper presents the results of research of the influence of chosen marine diesel engine fuel injection system faults on the shape of heat release characteristics. The study was conducted on a laboratory engine Sulzer Al25/30. The study was carried out according to active experiment plan, during which the selected engine failure of the injection system were simulated. Measurements of pressure of combustion were performed by means of tensometric sensors of Spice Company. Based on measured pressure curves heat release characteristics were determined. The algorithm allows the determination of heat release rate q and the generated heat Q characteristics. Based on the obtained results it can be concluded that significant improvement in the diagnostic use of indicator diagrams can be obtained by using heat release characteristics. These characteristics are correlated with the process of fuel injection and the injection pump operation. As demonstrated in the work of analyzing the heat release rate q, it is possible to infer diagnosis on the technical condition of the fuel injection system.

Keywords: *indicator diagram, heat release characteristics, marine diesel engine diagnosis*

Wpływ uszkodzeń układu wtryskowego okrętowego silnika tłokowego na przebieg charakterystyk wydzielania ciepła

Streszczenie: W artykule przedstawiono wyniki badań wpływu wybranych uszkodzeń układu wtryskowego silnika okrętowego na przebieg charakterystyk wydzielania ciepła. Badania przeprowadzono na laboratoryjnym silniku Sulzer typu Al25/30. Doświadczenie zrealizowano zgodnie z planem eksperymentu czynnego, podczas którego symulowano wybrane uszkodzenia układu wtryskowego. Indykowanie silnika wykonano za pomocą tensometrycznych czujników spalania firmy Spice. Wykorzystując uzyskane wykresy indykatorowe wyznaczono charakterystyki wydzielania ciepła. Zastosowania algorytmy umożliwia obliczenia szybkości wydzielania ciepła q oraz ciepła wydzielonego Q. W oparciu o uzyskane wyniki badań można stwierdzić, zastosowanie charakterystyk wydzielania ciepła, może w sposób istotny wpłynąć na podatność diagnostyczną wykresów indykatorowych. Potwierdzono istotną korelację pomiędzy działaniem układu wtryskowego a przebiegiem tych charakterystyk. W oparciu o uzyskane przebiegi szybkości wydzielania ciepła, możliwe diagnozowania badanych uszkodzeń układu wtryskowego.

Słowa kluczowe: *wykres indykatorowy, charakterystyki wydzielania ciepła, diagnozowanie silników okrętowych*

1. Introduction

In the shipbuilding industry there is a need for diagnostic systems to monitor the work processes in the piston engines cylinders and diagnostic inference based on indicator diagrams. In general, the greatest expectations in relation to diagnostic systems are associated with fault detection and forecasting the technical conditions of diesel engines.

The need for knowledge of the technical condition of the marine engines, arises from the need to maintain the safety of navigation, environmental protection and minimization of the cost of transportation. The selection of diagnostic information contained in the indicator diagrams and the credibility of the obtained information is a current and important issue .

It seems that the significant improvement in the diagnostic use of the indicator diagram can be obtained by designating the heat release characteristics. The purpose of the article was to evaluate the potential for the use of heat release characteristics to evaluate the technical condition of the injection system of marine diesel engines.

2. Heat release model for cylinder process diagnosis

Determination of the heat release dynamics is a complex mathematical and measuring problem [6].

The most important factors that determine the working process in the cylinder of an internal combustion engine include [1, 2]:

- charge exchange process;
- fuel injection process;
- cooling process;
- technical condition of the engine systems and elements.

The mentioned factors determine the heat release process. It can therefore be expected that the heat release characteristics provide information about the condition of fuel injection system.

Real sources of information about the technical condition can also be temperatures of exhaust gas from the cylinders and pressure curves measured on the indicator valves (indicator diagrams).

On the basis of diagnostic experience, one can conclude that diagnostic reasoning on the bases of the direct analysis of indicator diagrams can be done only in case of faults in an advanced stage of development. In the case of low-speed marine diesel engines, the measurement of fuel pressure in injection pipes can be done. Currently, the Kongsberg Company offers this possibility. Even in this case, the method does not guarantee that the observed deviation of the injection pressure has a significant impact on the process of combustion n.

Therefore, it seems advisable to use in the diagnosis of the injection system the heat release characteristics.

Measurement information in the form of indicator graphs does not allow for determination of heat of combustion, cooling losses, and losses of air charge and energy in the form of blows.

Therefore, the net heat release characteristics were adopted to use for diagnostic purposes. In the case of the single zone model indicator diagram is sufficient for net heat release characteristics determination.

Net heat release rate can be written as follows:

$$dQ_n = dQ_{sp} - dQ_{ch} - \sum dm_i h_i = dU + dW \qquad (1)$$

where:
dQ_n – net heat release rate,
dQ_{sp} – heat of combustion,
dU – change in internal energy,
dW – work done by the system,
dQ_{ch} – heat exchange with the walls,
dm_i – amount of a substance listed by the boundaries of the system: blow, and the fuel (exhaust gas generation),
h_i – specific enthalpy.

Assuming isentropic transformation and assuming $\sum dm_i h_i = 0$, equation (1) takes the form [3]:

$$dQ_n = \frac{\kappa}{\kappa - 1} pdV + \frac{1}{\kappa - 1} Vdp \qquad (2)$$

where: κ = cont – isentropic exponent.

The net heat release rate in the crank angle domain is as follows:

$$dQ_n = \frac{dQ_n}{d\alpha} = \frac{\kappa}{\kappa - 1} p\frac{dV}{d\alpha} + \frac{1}{\kappa - 1} V\frac{dp}{d\alpha} \qquad (3)$$

where:
α– crank angle.

Net heat released for a given angle α position of the shaft from the BDC is calculated by the formula:

$$Q_n = \int_0^\alpha q_n d\alpha \qquad (4)$$

Simplification that a charge in the cylinder is ideal gas introduced essentially constant errors almost the same for each cylinder in a given load. It is assumed that this does not affect the level of diagnostic symptoms.

3. Experiment methodology

The aim of the experiment was to investigate the effect of selected engine fuel injection system faults on the shape of net heat release characteristics. An additional aim was to evaluate potential use of the characteristics for diagnostic purposes.

The tests were conducted in a laboratory test bed post of four-stroke marine engine, type Sulzer 3Al 25/30, with nominal power N_{en} = 408 kW at nominal rotational speed n = 750 rpm (Fig. 1).

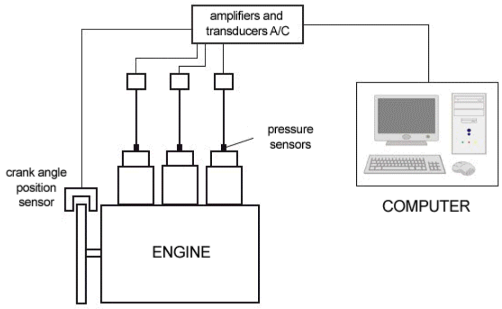

Fig. 1. Laboratory experimental stand

The curves of indicator diagrams have been recorded with an electronic indicator Unitest 205 with angular resolution of 0.5 ^{o}OWK for pressure measurement, one has used tensometric pressure sensors from Spice Company. The curves of pressure were averaged for 16 work cycles.

The engine indication was conducted at load N_e = 240 kW, which, with regard to nominal load, corresponds approximately to 70 % N_{en}. In order to increase the credibility of the test results, the research experiment was conducted twice.

After each load change, the tester waited for the period necessary to determine a thermodynamic balance of the engine, following the stabilization of flue gas temperatures and cooling factors.

The research program was conducted according to active experiment principles. During the experiment, each time, one level of particular malfunction was simulated and all parameters were measured. The experiment excluded simultaneous presence of multiple malfunctions, as well as, different ranges of particular malfunction.

The following malfunctions were taken into account:

- injection pump leakage;
- clogged injector nozzles;
- diminished injector opening pressure.

Figure 2 shows examples of pressure curves for the simulated fuel system faults.

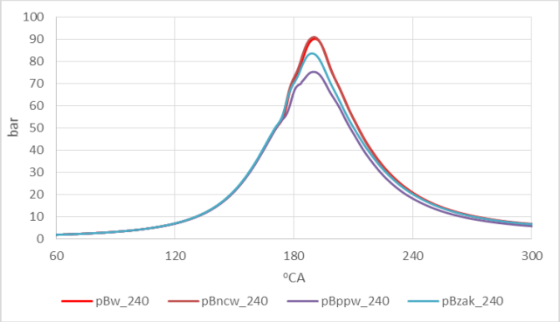

Fig. 2. Sample indicator curves registered on the engine 3AL25/30: pBw_240 – reference curve for the state without faults (nominal) , pBncw_240 – diminished injector opening pressure, pBppw_240 – injection pump leakage, pBzak_240 – clogged injector nozzles

Heat release characteristics were determined on the basis of equation (3) based on real indicator diagrams.

Determination of released heat Q requires the integration of the value of q in the field crank angle, from the piston BDC.

In this work the net heat release rate and net heat released are related to a cylinder volume. In this case the unit of heat release is pressure.

In order to determine the heat release characteristic as well as MIP values thermodynamic TDC was used which was calculated with the original method based on polynomial model of compression curve exponent [4], [5].

4. Test results analysis

4.1. Influence of injection pump leakage simulation on the shape of net heat release characteristics

Figure 3 shows the curve of net heat release rate calculated for the simulation of the injection pump leaks increase. Curve for simulated curve highlighted in red is related to reference curve for nominal state (without simulation) for the load of 240 kW.

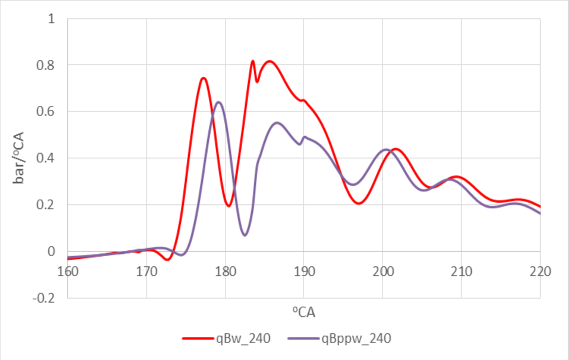

Fig. 3. Net heat release rate: qBw_240 – reference curve for the state without faults (nominal) , qBppw_240 – curve for injection pump leakage

Presented curves very well illustrate the potential diagnostic use of the net heat release rate. Delay in beginning of combustion is clearly visible and is about 2.5 ^{o}CA, compared to reference curve. The smaller intensity of heat release in the entire combustion process can be also observed. The value of the maximum heat release rate is equal to 0,64 bar/^{o}CA and is about 22% lower than the reference value. It is possible to mark contractual points of the beginning and the end of combustion, and the same duration of the process can be determined.

For the same simulation, the shape of heat released was shown in Figure 4. Heat released curves in turn can be used to analyse the intensity of reaching the maximum value of generated heat, which can be seen as a moment of end of the combustion.

In relation to test injection pump leakage simulation maximum of generated heat was 17.9 bar compared to a reference value 22.9 bar. Based on the curves, it is also possible to identify point of exhaust valve opening.

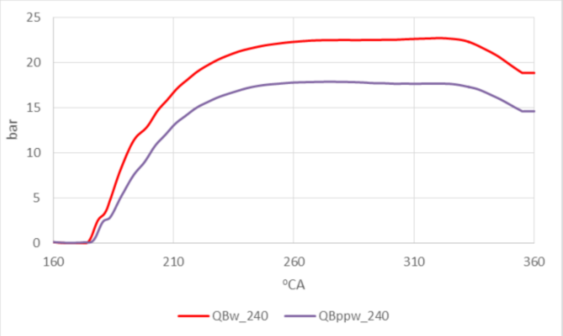

Fig. 4. Net heat released: QBw_240 – reference curve for the state without faults (nominal), QBppw_240 – curve for injection pump leakage

4.2. Influence of clogged injector nozzles simulation on the shape of net heat release characteristics

Figure 5 shows the curve of net heat release rate calculated for the simulation of clogged injector nozzles. The simulation consisted in that the five of seven holes in injector nozzles were clogged - resulting in a smaller amount of fuel was fed into the cylinder.

In the case of this simulation is important that in the initial stage of combustion takes place it correctly - the lid with a reference value. This means that the delay of injection angle of was the correct and at initial stage of combustion, simulation had no significant influence on the shape of heat release.

Lower intensity of combustion process takes place scarcely in the second period, when less fuel is fed into the cylinder. Lower maximum heat release rate can be seen in both the first and second period of combustion.

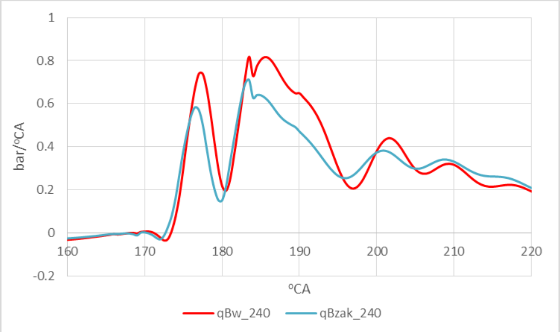

Fig.5. Net heat release rate: qBw_240 – reference curve for the state without faults (nominal) , qBzak_240 – curve for clogged injector nozzles

Confirmation of the mentioned symptoms of the simulation is also apparently on the shape of released heat (Fig. 6). Beginning burning is correct, it is only after about 175 °CA takes less steeply than the standard process and achieves a lower maximum value 21.4 bar, which is a decrease compared to the reference value about 6%.

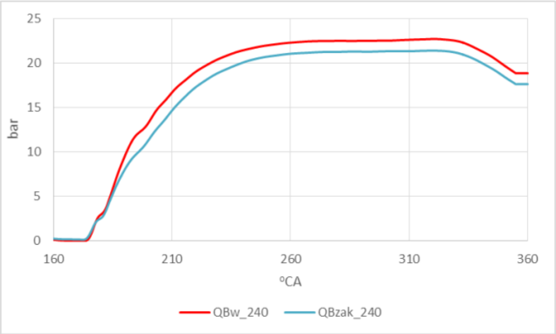

Fig. 6. Net heat released: QBw_240 – reference curve for the state without faults (nominal) , QBzak_240 – curve for clogged injector nozzles

4.3. Influence of diminished injector opening pressure simulation on the shape of net heat release

Figure 7 shows the curve of net heat release rate calculated for the simulation of diminished injector opening pressure. The simulation was based on the reduction of the injector opening pressure from nominal 250 bar to 150 bar. This kind of fuel injector faults is often found in practice damage due to a reduced rigidity of the injector spring.

Phase shift of the combustion process towards the left can be seen, and a minimal increase in maximum heat release rate. The offset phase of combustion process is probably due to the lower injector opening pressure. The fuel injection into the cylinder is in advance, and the result of that is faster to start the combustion process. Phase shift of combustion is negligible and is about 0,5 °CA.

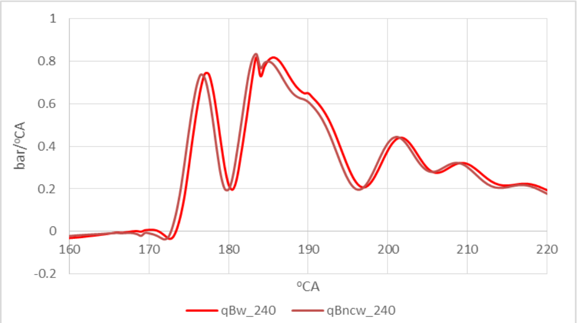

Fig. 7. Net heat released: qBw_240 – reference curve for the state without faults (nominal), qBncw_240 – diminished injector opening pressure simulation

No significant symptoms of simulate faults confirms the net released heat, which is shown in Fig 8. Minor deviations from the reference sequence are visible only in the final stage of combustion. Max value released heat was 22 bar, the reference values for of 22.7 bar. The difference was therefore 3%.

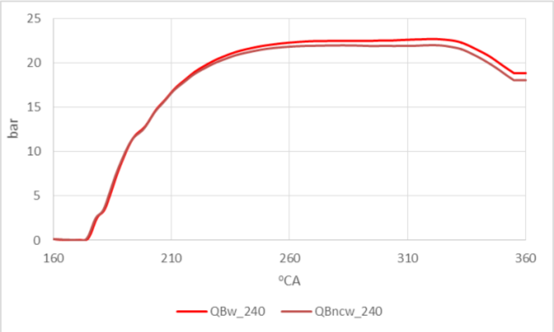

Fig. 8. Net heat released: QBw_240 – reference curve for the state without faults (nominal), QBncw_240 – diminished injector opening pressure simulation

5. Conclusions

Diagnostic reasoning based on a comparison of indicator diagrams and the variation of maximum combustion pressure within the 5% and even 10% is very difficult. The diagnosis in this case is limited to an occurrence of significant deviations without specifying of its reasons. This conclusion is confirmed by the results of analyzes of indicator diagrams taken for other engines, ships and pressure analyzers.

Improvement of diagnostic inference based on indicator diagrams, can be obtained by analyzing the characteristics of the net heat release rate, determined on the basis of indicator diagrams. Heat release characteristics allows the observation of the angular amplitude variation associated with the operation of the injection systems.

Based on the obtained results it can be concluded that based on the determined heat released characteristics, it is possible to isolate individual symptoms of surveyed failures the injection system, which will enable them to be identified.

Nomenclature/*Skróty i oznaczenia*

TDC	Top Dead Center/*górne martwe położenie tłoka*
^{o}CA	Crang Angle Position/*stopień obrotu wału korbowego*
ΔQ_s	heat of combustion/*ciepło wydzielone na skutek spalania*
dU	change in internal energy/*zmiana energii wewnętrznej*
ΔW	work done by the system/*praca wykonana przez układ*
ΔQ_w	heat exchange with the walls/*ciepło wymienione ze ściankami*
dm_i	amount of a substance listed by the boundaries of the system: blow, and the fuel (exhaust gas generation)/*ilość substancji wymienionej przez granice układu: przedmuchy i doprowadzenie paliwa (generowanie spalin)*
h_i	specific enthalpy/*entalpia właściwa*
κ	isentropic exponent/*wykładnik izentropy*

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