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INFLUENCE OF CLOGGED INJECTOR NOZZLES ON THE HEAT RELEASE CHARACTERISTICS

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Abstract

The paper presents the results of research of the influence of clogged injector nozzles in fuel injection system on the shape of heat release characteristics. The study was conducted on a laboratory four-stroke marine engine, type Sulzer 3Al 25/30, with nominal power N_e = 408 kW at nominal rotational speed n = 750 rpm. The study was carried out according to active experiment plan, during which the engine failure of the injection system was simulated. Simulation of loss of patency of injector nozzles (clogged) was to completely clog two holes of nine injection injector nozzle holes with a diameter of 0,325 mm. Measurements were made at a constant engine speed of 750 rev/min for five loads: 50, 100, 150, 200, 250 kW. 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 net heat release rate q and the net 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 analysing 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*

1. Introduction

Partial or complete clogging of injection holes as a result of their coking is one of the most common faults of injection systems of marine engines, especially working on heavy fuel. This failure, as a result of pressure increase in the injection system can lead a leakage in the fuel system or even rupture of the injection pipe. From personal experience, is known the case of a break away injector nozzle as a result of clogging the holes of medium speed engine. The consequence of flight (blow out) the injector nozzle through the exhaust duct was knock off a small piece of a turbine blade, which caused the rotor imbalance, vibration increase and rapid destruction of the bearings.

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 [2], [3].

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 [4],[5].

2. Preparation and conduct simulation research

The tests were conducted on a four-stroke laboratory marine diesel engine, type Sulzer 3Al 25/30, with nominal power N_e = 408 kW at nominal speed n = 750 rpm.

Simulation of loss of patency of injector nozzles (clogged) was to completely clog two holes of nine injection injector nozzle holes with a diameter of 0.325 mm. As a result of loss of patency by some holes the speed of flow through the remaining holes will increase, due to the continuity equation determined by kinematics movement of the pump plunger.

Increased flow speed can push the limits of a flame creation to the injector nozzles, which would increase its temperature and the possibility of further loss of patency [7]. Increased flow speed would also increase the loudness of fuel stream, and an increase in local temperature of the engine piston and cylinder and consequently increase of their thermal stress. The occurrence of these phenomena depends on the design parameters of the injection system and the injection process and parameters prevailing in the cylinder. It can be expected deterioration in the quality of fuel atomization, which may lead to reduced efficiency of the engine internal cycle.

A series of measurements for the nominal state (reference) and the state of the damage was done. Measurements were made at a constant engine speed of 750 rev/min for five loads: 50, 100, 150, 200, 250 kW.

The curves of indicator diagrams have been recorded with an electronic indicator Unitest 205 with angular resolution of 0.5°CA. Tensometric pressure sensors from Spice Company were used for pressure measurement. The curves of pressure were averaged for 16 work cycles.

The article presents the measured values and curves only for two loads, due to the limited perception of a large number of curves on one figure.

Analysed parameters for the nominal (reference) state, in addition to the maximum rate of pressure rise p'_{max} are linearly dependent of the mean indicated pressure (Fig. 1).

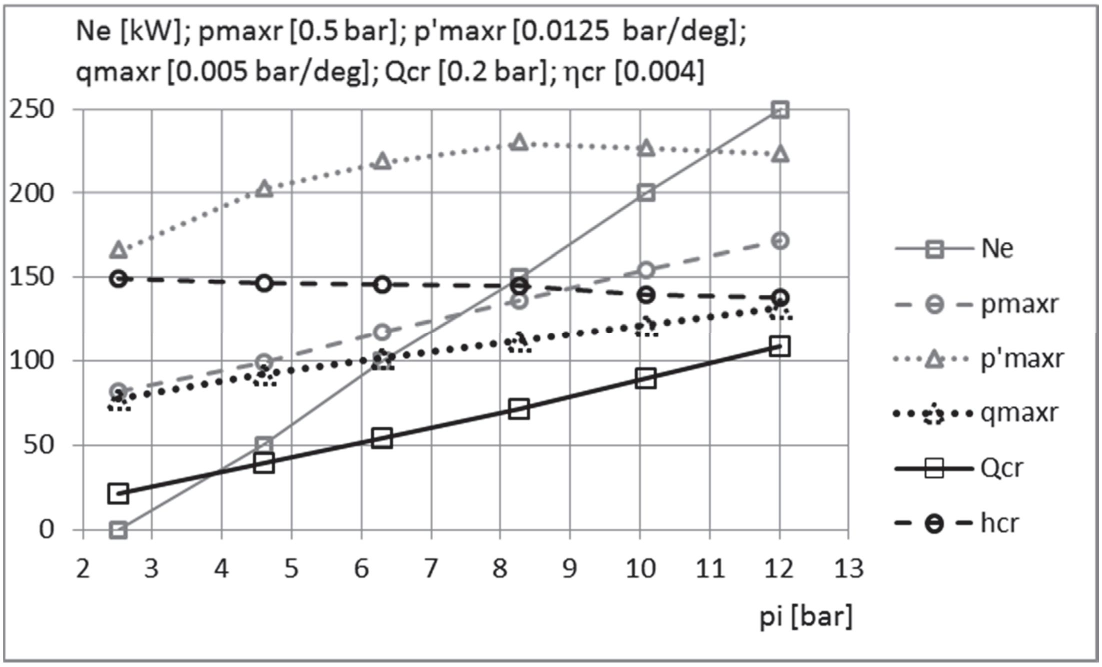

Fig. 1. Dependence of the analysed parameters from the mean indicated pressure for the nominal state: N_e – effective power (engine load), p_{maxr} – maximum combustion pressure, p'_{maxr} – maximum rate of pressure rise, q_{maxr} – the maximum value of the net heat release rate, Q_{cr} – net heat generated cycle, η_{cr} – net internal efficiency of the cycle

The only parameter that does not have a linear relationship is the maximum rate of pressure rise p'_{maxr} that for pi = 8.3 bar reaches the maximum value and further maintains constant.

3. Infuence of cloggedinjector nozzels on the indicator diagram parameters

Mean indicated pressure drop and accompanying it decline in the value of the maximum pressure is observable symptom of loss of patency (clogging) of injection nozzles (Fig. 2).

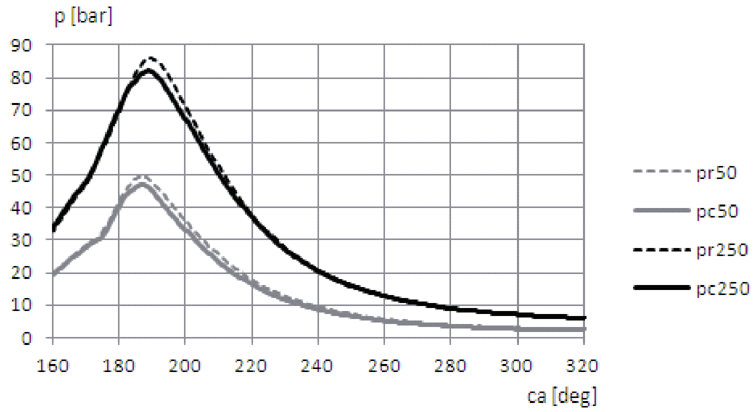

Fig. 2. Comparison of the indicator diagram for the reference state (pr50; pr250) and the state of clogging nozzles (pr50; pr250) for engine power 50 kW and 250 kW

Table 1 compares the percentage maximum combustion pressure drop and mean indicated pressure caused by clogging of injection nozzles for different loads. The deviations were determined from the following formulas:

$$\delta p_{max} = \frac{p_{maxr} - p_{maxc}}{p_{maxr}} 100\ [\%]\ ;\ \delta p_i = \frac{p_{ir} - p_{ic}}{p_{ir}} 100\ [\%], \qquad (1)$$

where: r is the index of the nominal state, and the index c is the index of simulation of the clogged injection nozzles.

Tab. 1. Declines of mean indicated pressure δp_i and the maximum combustion pressure δp_{max} due to simulated clogged injection nozzles, related to the nominal (reference) values

N_e [kW]	50	100	150	200	250
δp_i [%]	15.7	12.7	11.9	9.8	5.4
δp_{max} [%]	5.4	5.4	5.7	6.0	4.6

If, however, considered the maximum pressure drop as a function of mean indicated pressure (Fig. 3), the result are closely to cylinder load drops, which should be associated with a reduction in the amount of fuel.

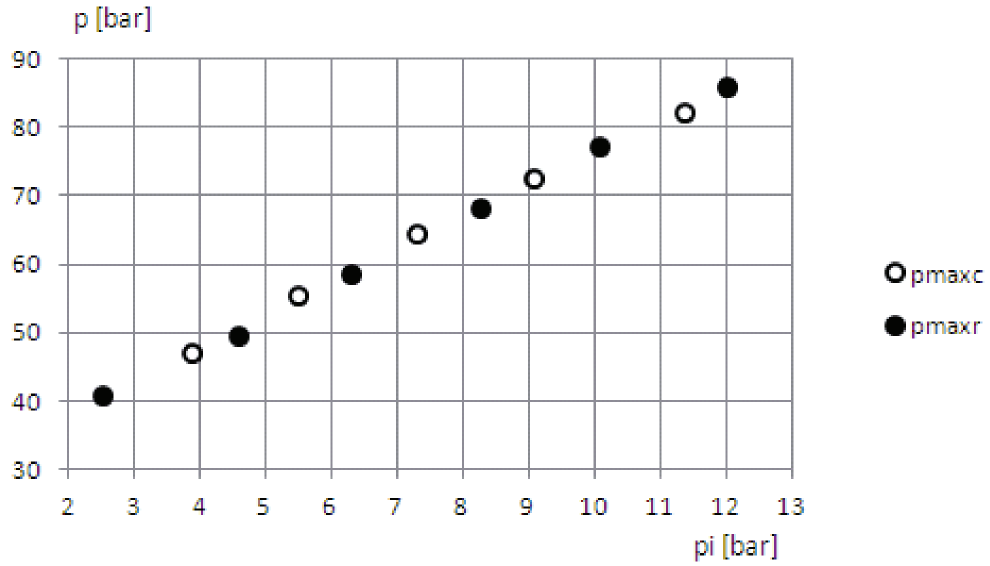

Fig. 3. Comparison of the maximum pressure in the cylinder as a function of mean indicated pressure p_i: p_{maxc} – simulation, p_{maxr} – reference state

Sometimes for diagnostic purposes of the injection systems the analysis of the first order derivative of pressure are used. For the simulation study, some differences were observed in the derivative of pressure for the load of 250 kW (Fig. 4).

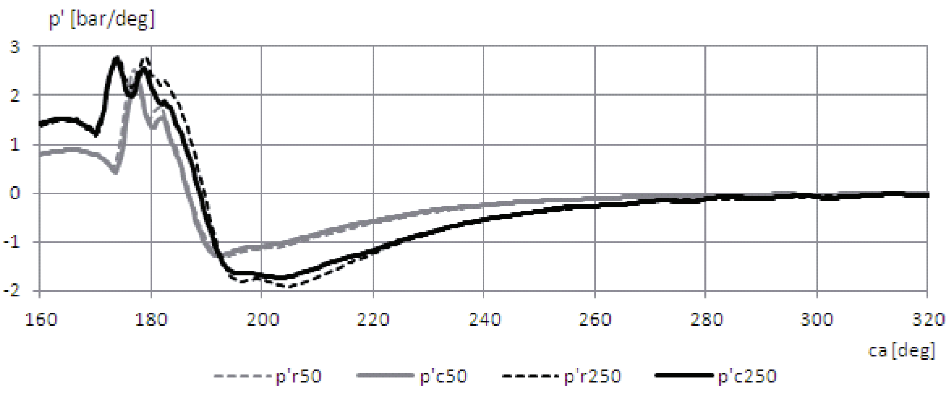

Fig. 4. Comparison of the first order derivatives of pressure for the nominal state (p'r50; p'r250) and the state of clogged injector nozzles (p'c50, p'c250) for specific loads 50 kW and 250 kW

The above symptom occurred for all investigated load reducing gradually with load decreasing (Fig. 5).

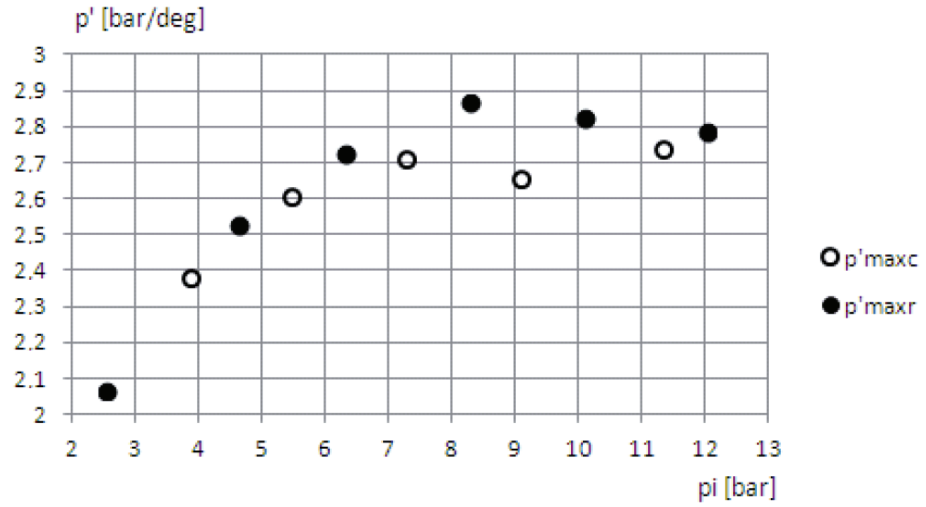

Fig. 5. Comparison of the rate of maximum pressure rise in the cylinder as a function of mean indicated pressure p_i: p'_{maxc} – simulation, p'_{maxr}–reference state

For engine load $p_i < 6.5$ bar/deg efficiency courses overlap.

The above symptom occurred at all tested loads gradually decreasing with decreasing load. For a load of 50 kW curves p' practically coincide.

In this case, direct reference of the mean indicated pressure and the maximum combustion pressure to the nominal state provides more reliable diagnostics inference. However, it should be noted that the decrease in symptoms similar to the mean indicated pressure and the maximum combustion pressure might also be caused by leaks in the fuel injection system or regulation errors.

4. Analysis of the impact of clogged injector nozzles on the net heat release characteristics

Determination of the heat release dynamics is a complex mathematical and measuring problem [6], [1]. Assuming isentropic transformation the net heat release rate q can be stated in the form

[6]:

$$q = \frac{\kappa}{\kappa-1} pdV + \frac{1}{\kappa-1} Vdp, \quad (2)$$

where:
κ = cont – isentropic exponent,
p – pressure,
V – cylinder volume.

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

$$Q = \int_0^{\alpha} q d\alpha, \quad (3)$$

where q-net heat release rate.

Simulation of clogged injector nozzles resulted in decrease of the total amount of net generated heat, uniformly in the angular range above 190°CA (Fig. 6).

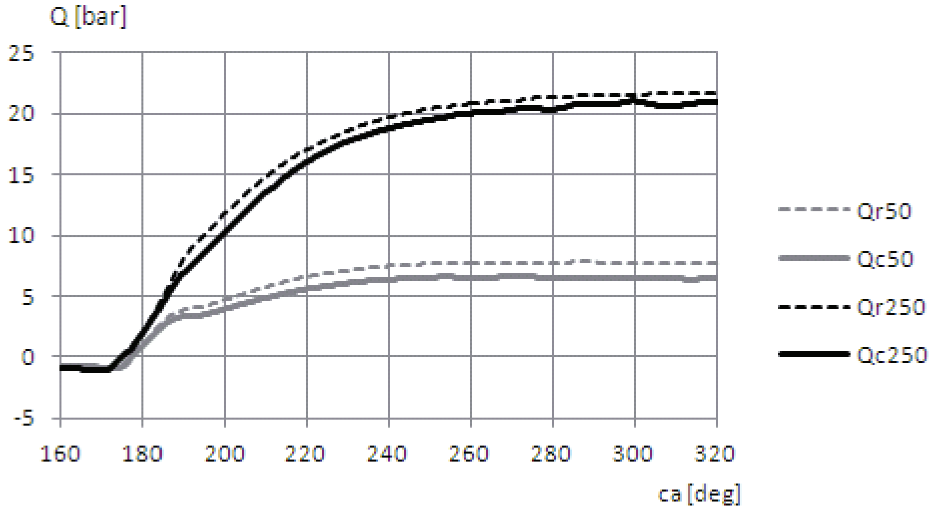

Fig. 6. Comparison of the net generated heat Q for the nominal state (Qr50; Qr250) and the state of clogging nozzles (Qc50; Qc250) for specific loads 50 and 250 kW

The above Q decreases, however, are the result of a fuel dosage reduction, which discloses a comparison of the values of Q as a function of mean indicated pressure p_i (Fig. 7).

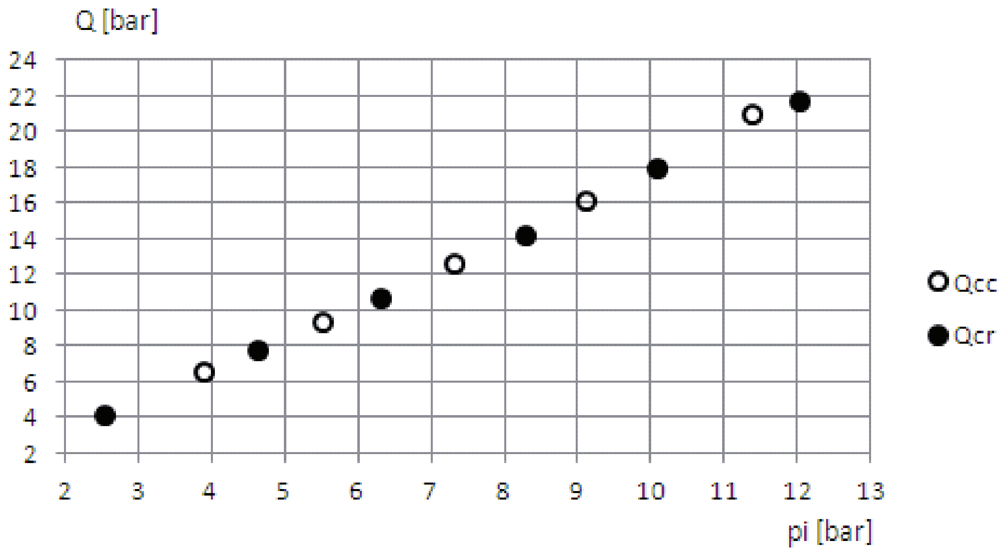

Fig. 7. Comparison of the net generated heat Q as a function of mean indicated pressure pi: Qcc – simulation, Qcr – reference state

The same curves and differences were obtained for the other loads. The observed differences cannot be therefore the basis for reasoning about their reasons.

Better results are obtained by analysis of net heat release rate, which is observed (Fig. 8) a significant reduction in the amplitude of the net heat release rate q for the load of 250 kW.

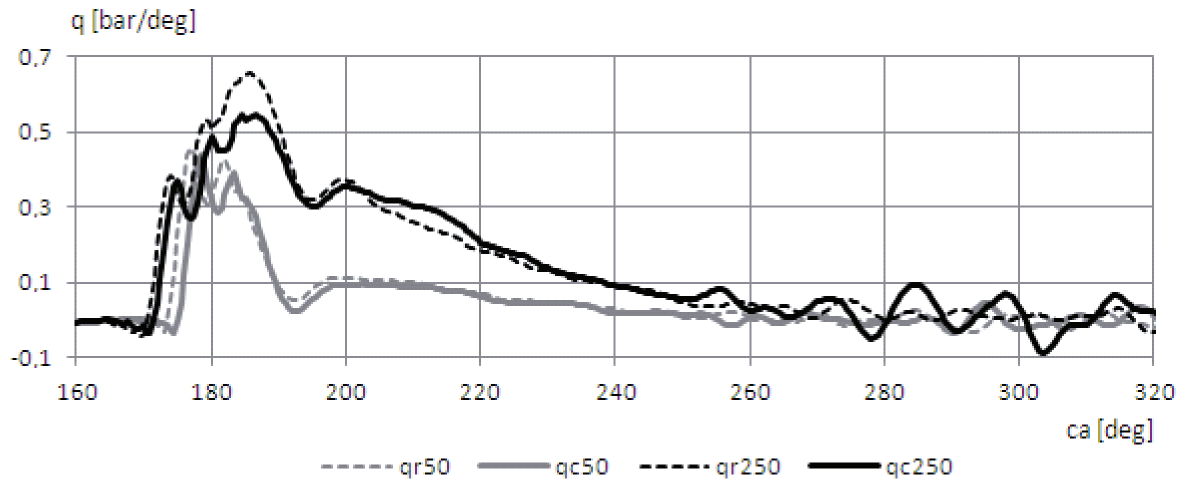

Fig. 8. Comparison of the net heat release rate q for the nominal state (qr50; qr250) and the state of clogged injector nozzles (qc50; qc250) for specific loads 50 kW and 250 kW

Percent differences of δq_{max} value decreases with decreasing load (Table 2).

Tab. 2. The percentage decrease of the maximum net heat release rate δq_{max} caused by clogging of injection nozzles

N_e [kW]	50	100	150	200	250
δq_{max} [%]	4.4	7.1	13.2	13.6	16.8

Comparison of maximum net heat release rate q in mean indicated pressure domain p_i (Fig. 9) indicates a decreases of q_{max} for p_i> 5 bar (Fig. 9).

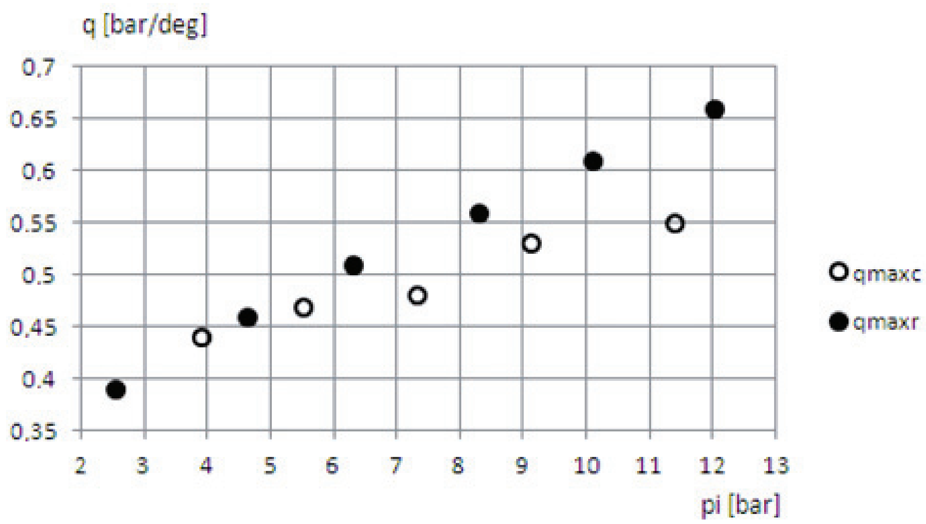

Fig. 9. Comparison of the maximum of net heat release rate q as a function of mean indicated pressure p_i: q_{max} – simulation, q_{maxr} – reference state

It is expected that information of the quality of the injection process and subsequently the accuracy of combustion can provide a net cycle internal efficiency η_{wn}. Net cycle internal efficiency is defined as follows:

$$\eta_{wn} = \frac{p_i}{Q_{max}}, \tag{4}$$

where:

p_i – mean indicated pressure,

Q_{max} – maximum of net released heat.

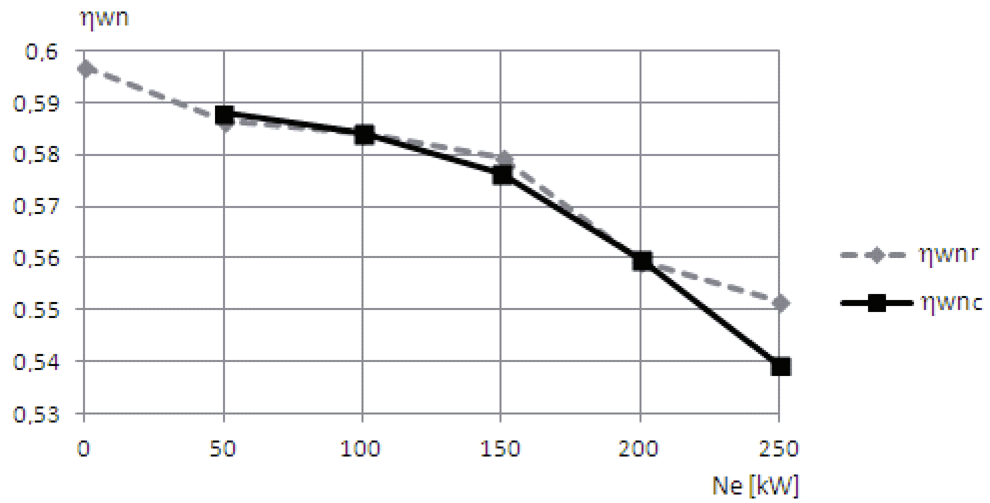

Fig. 10. Comparison of net cycle internal efficiency η_{wn} for the nominal state (η_{wnr}) and simulation (η_{wnr}) as a function of engine load

As shown in the diagram (Fig. 10) net cycle internal efficiency for the load 200 kW and below are equal or deviations are not significant. It is quite possible that this parameter can contain diagnostic information for the engine loads larger than 200 kW. Decrease in net cycle internal efficiency may indicate extended burning due to malfunction of the injector.

Comparison of the efficiency values η_{wn} in the field of mean indicated pressure indicates its decline with increasing p_i (Fig. 11).

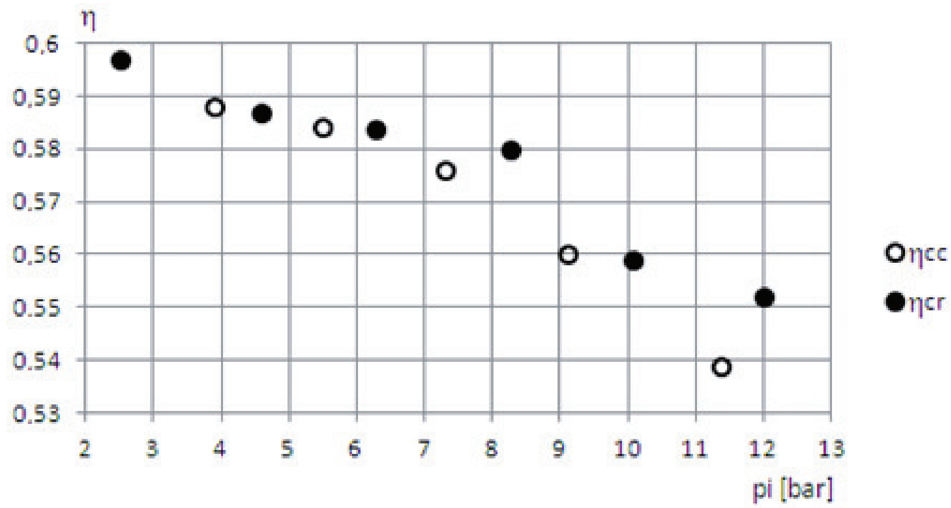

Fig. 11. Comparison of the net internal efficiency as function of mean indicated pressure pi: η_{cc} – simulation, η_{cr} – reference state

5.Conclusions

The parameters that can be used in the diagnosis of clogged fuel injection nozzles are: maximum combustion pressure p_{max}, mean indicated pressure pi, the maximum net heat release d_{qmax} and net internal efficiency η_{wn} for higher range of loads.

As a result of clogging nozzles showed a decrease in fuel delivery per cycle and reduce the mean indicated pressure and maximum combustion pressure.

Significant symptoms of o clogging nozzles are also decrease of the maximum net heat release rate and internal efficiency drop for the higher values of mean indicated pressure.

Comparative symptoms analyzes of different faults of the fuel injection system are needed for identifying symptomatic method to distinguish these failures.

It is desirable to also record the temperature and compositionof exhaust gases to explain the extent to which disability affects the combustion process. It is planned to measure and record these values in subsequent studies, as well as supporting the use of vibration of the fuel injectors.

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