ANALYSIS OF PERFORMANCES OF A DUAL-FUEL TURBOCHARGED COMPRESSION IGNITION ENGINE

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Abstract

The paper describes research work on a full-scale dual-fuel 4-cylinder turbocharged compression ignition engine. Compressed natural gas (CNG) was applied as the main fuel. Selfignition of the air-fuel mixture was initiated from a diesel oil dose injected by a common rail system. The research was aimed to establish maximum CNG share in the mixture delivered into the cylinder. An excessive CNG share may result in "hard" engine operation. It may also lead to the occurrence of vibrations of piston-crank construction parts resulting in failure of this mechanism. These vibrations may originate from knocking combustion (selfignition of the air-fuel mixture in the zone of non-combusted mixture) or vibration excitation as a result of rapid pressure rise after selfignition.

Boundary values of the CNG energy share were determined by analysing parameters related to the rate of pressure rise and rate of heat release as well as the engine head vibration amplitude represented by the voltage signal generated by the knock sensor.

Boundary values of the above mentioned parameters were determined on the basis of measurements done on the engine fuelled in a standard mode. These parameters were registered at operating points corresponding to the maximum power and load.

Then, there were done measurements of basic engine operating parameters at dual fuelling in chosen points of the load characteristic for the engine speed at which the engine fuelled in a standard mode had maximum torque. Load characteristics were done for three various diesel oil doses (constant over the whole range of engine load). Load changes were realized by changes of CNG energy share in the fuel charge.

Analysis of combustion process parameters and engine head vibrations showed that CNG energy share may reach 60%. Maximum torque is possible to obtain at 45% CNG energy share. 15% decrease of maximum torque was obtained.

Keywords: *dual fuel compression ignition engine, knock, engine head vibration amplitude, compressed natural gas (CNG), common rail*

1. Introduction

The commonly observed tendency to limit consumption of fossil fuels led to higher interest in application of alternative fuels to combustion engines. One of such fuels is natural gas [1]. Application of natural gas to combustion engines is limited by its distribution. For this reason, there are preferred solutions that allow the engine to run on one fuel (conventional or alternative) as well as on dual fuels (simultaneously on both fuels or on diesel oil only) [2]. The first mentioned solution is widely applied in spark ignition engines and the second – in compression ignition engines. Dual fuelling of CI engine consists in an injection of small diesel oil dose that initiates gas combustion. Diesel oil is delivered by conventional injection system. Gas fuel may be delivered into the intake manifold (indirect injection) or into the cylinder (direct injection).

The paper presents results of the study on possible co-operation of the common rail system with indirect CNG injection. Investigation was carried out within the framework of a research project [3] focused on adaptation of a turbocharged engine to dual fuelling with diesel oil and natural gas. The primary purpose of the carried conducted research was to establish the optimal energy share ratio of diesel oil and CNG in the fuel charge delivered into the cylinder. The optimization was aimed to achieve engine external parameters close to the nominal ones given by the engine manufacturer at maximally high CNG energy share. Quantity of fuels delivered to the engine was controlled by two independently operating fuel systems. Diesel oil pilot dose was delivered by factory common rail system. CNG was delivered by a multipoint indirect injection system developed within the framework of the research project [3].

Regulating parameters obtained as a result of the optimization (CNG energy share and pilot dose quantity) allowed achieving torque values comparable to those obtained at factory fuelling over the whole range of the engine speed. CNG energy share in the fuel charge delivered into the cylinder reached 60%. The values of overall efficiency were comparable for the same engine operating parameters and reached 40%.

Investigation was carried out at the engine speed corresponding to the maximum torque. For the tested engine it was N = 2000 rpm. Diesel oil delivery was adjusted in such way to ensure engine operation at the following loads: T = 20Nm (BMEP = 0.1 MPa), T = 40 Nm (BMEP = 0.21 MPa) and T = 100 Nm (BMEP = 0.52 MPa). The adjustment was realized by proper accelerator pedal deflection. The remaining part of load was obtained by increasing CNG quantity delivered into the cylinder up to a distinct decrease of engine overall efficiency and increase of engine noise being a symptom of abnormal engine operation (knock or "hard" combustion). Further increase of CNG share allowed to obtain loads that exceeded by ca. 20 Nm loads of the engine fuelled in a standard mode. However, the engine operated "hard" with audible knock.

Verification of these results over the whole range of the engine operation should be the reason to build an integrated controller enabling easy adjustment of the factory common-rail fuel system to dual fuelling.

2. Test stand

The investigation was carried out on the test stand (Fig. 1) equipped with a turbocharged compression ignition Andoria ADCR engine and the electro-rotational brake manufactured by Automex. The engine technical parameters are presented in Tab. 1.

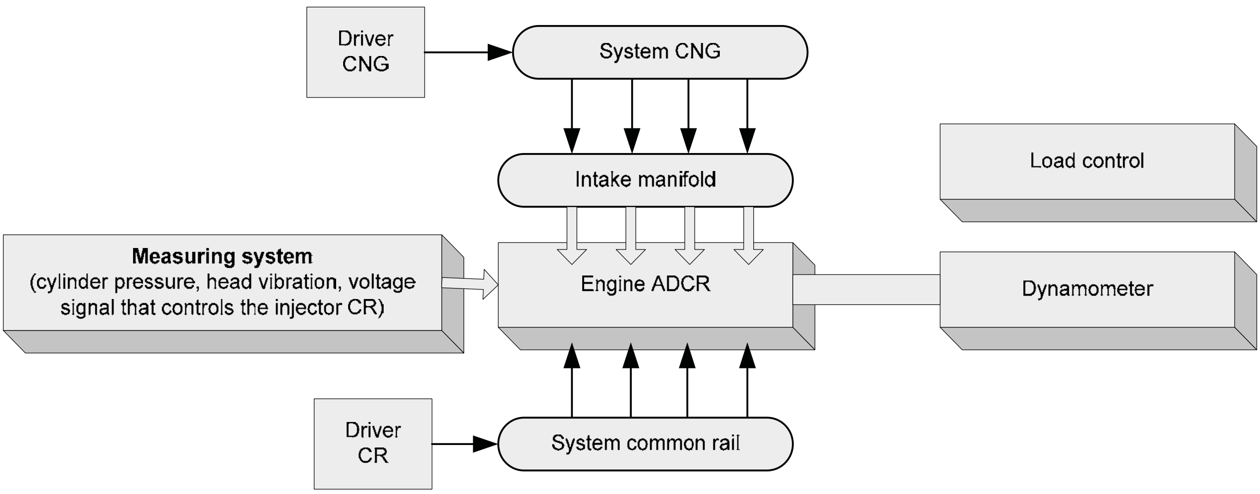

Fig. 1. Block scheme of the test stand

Fast-changing parameters were measured using a system described in [4], that is equipped with Keithley KPCI-3110A data acquisition board that enables the user to sample data at speeds up to 1.25 MHz, cylinder pressure measurement track with the AVL 8Qp500c piezoelectric sensor, 2channel crank angle indicator (initiation of single measurement every 0.7 C.A. and measurement cycle – with TDC indicator) and engine head vibration measurement track with OPEL DR 190 8092-2F sensor.

Tab. 1. Technical parameters of the ADCR engine

Type	Compression ignition, Common-Rail, turbocharger, direct injection
Number of cylinder	4
Bore	94 mm
Stroke	95 mm
Engine capacity	2636 cm^3
Compression ratio	17.5
Maximum power	85 kW/3700 rpm
Maximum torque	250Nm/(1800-2200obr/min)

3. Investigation on the engine with the factory fuel system

In order to evaluate the possibility of dual fuelling of the ADCR engine, dynamometric testing was carried out. There were registered: power, torque, fuel consumption and cylinder pressure at standard fuelling (common rail system). On the basis of the obtained results the speed characteristic was prepared (Fig. 2). It results from this characteristic, that the engine achieves maximum torque and efficiency at the speed of about 2000 rpm and maximum power at the speed of 3700 rpm.

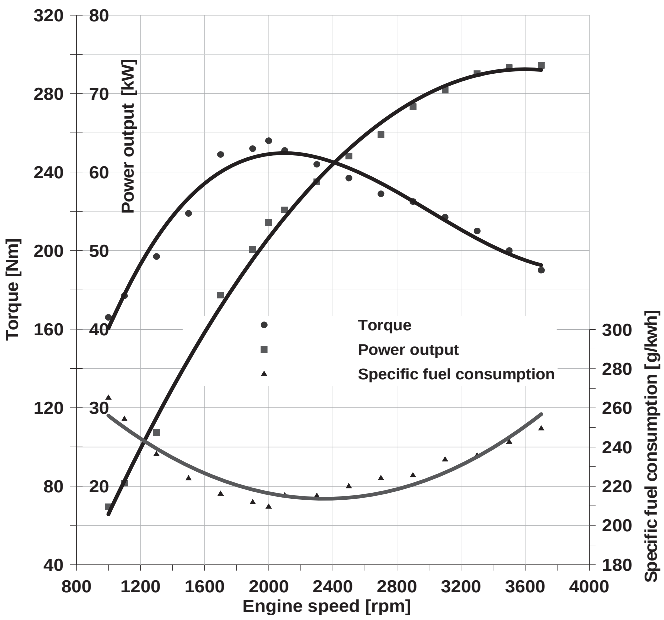

Fig. 2. Speed characteristics

Dual fuelling may lead to an excessive increase of values of parameters that determine engine durability. These parameters are:

- maximum operating pressure,
- rate of pressure rise,
- rate of heat release,
- pressure pulsations,
- vibrations of engine construction parts.

In order to assess boundary values of these parameters, measurements of cylinder pressure and head vibrations at the operating point corresponding to the full load (n = 2000 rpm and T = 250 Nm) were done.

Cylinder pressure measurements were the basis to calculate chosen combustion process parameters, such as: maximum pressure, rate of pressure rise and rate of heat release. Engine head vibrations were determined analysing the amplitude of the voltage signal generated by the knock sensor. Fig. 3 presents pressure courses and corresponding rates of pressure rise at the engine speed N = 2000 rpm (speed of maximum torque). The plots allow determining permissible (maximum) cylinder pressure values and maximum rates of pressure rise $(dp/d\varphi)_{max}$. Maximum combustion pressures are about 10 MPa while rates of pressure rise are below 0.3 MPa/C.A. Such conditions may be obtained by proper fuel injection control (fuel dose distribution and angles of injection start of individual doses) realized by the factory common rail system. At the point corresponding to maximum torque, fuel dose injection is divided into three parts while at the point corresponding to maximum power – into two parts.

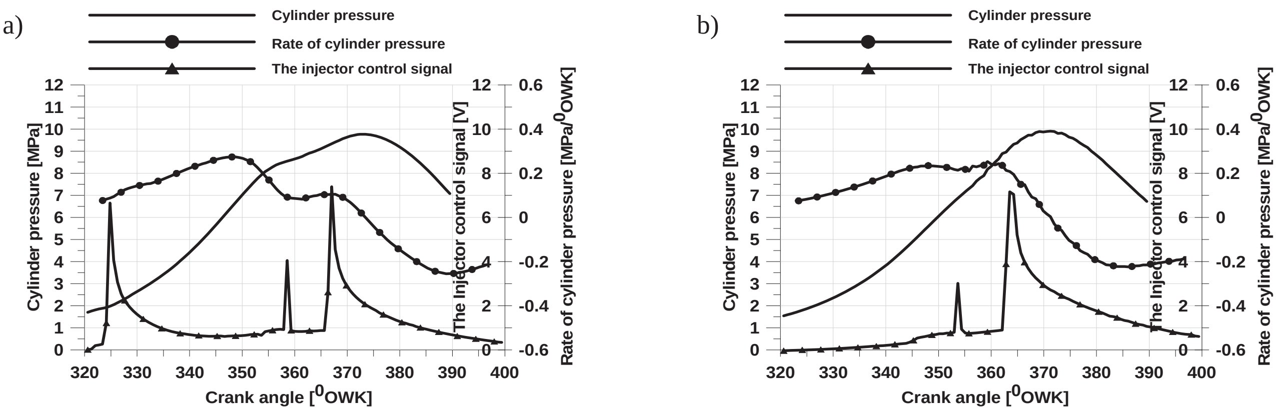

Fig. 3. Cylinder pressure changes, rate of cylinder pressure rise and the injector control signal, for: a) 2000 rpm (P = 54 kW, T = 256 Nm, BMEP = 1.32 MPa) and b) 3700 rpm (P = 74 kW, T = 210 Nm, BMEP = 1.08 MPa)

To calculate the rates of heat release, a relationship resulting from the first law of thermodynamics was applied, neglecting heat losses. Calculation results are presented in Fig. 4. Additionally, Fig. 4 presents also voltage signal amplitude generated by the knock sensor.

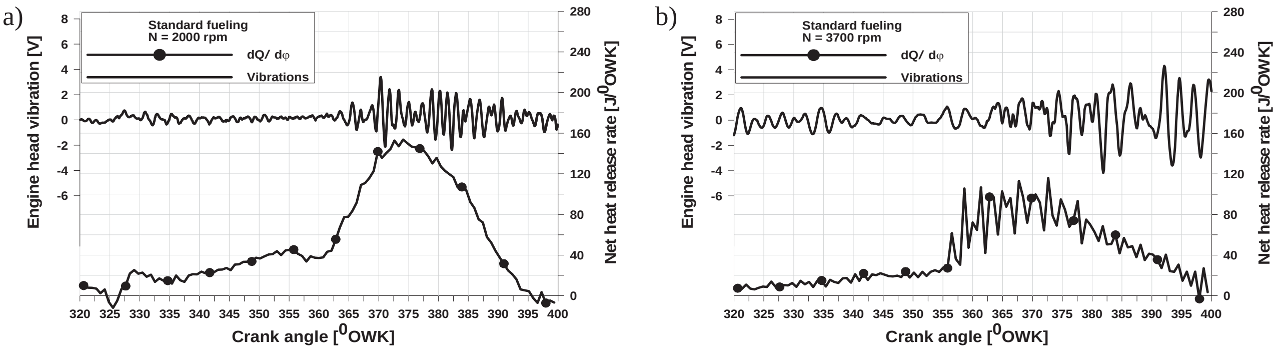

Fig. 4. Heat release and engine head vibration at standard fuelling: a) N = 2000 rpm, b) N = 3700 rpm

Runs of heat release at both operating points were free from the phase of violent kinetic combustion, typical for CI engines. Absence of the phase of kinetic combustion results also from proper fuel injection control. The engine head vibration amplitude expressed by the voltage signal generated by the knock sensor does not exceed 4.5 V. This concerns also vibrations generated by remaining engine cylinders. Thus, this level may be regarded secure.

4. Investigation on a dual-fuel engine – factory fuel system and indirect CNG injection

Final evaluation of the possibility of simple adaptation of the ADCR engine to dual fuelling was based on the concept assuming co-operation of the factory common rail fuel system with the indirect CNG injection system. In connection with this, a series of tests was carried out. They consisted in an increase of CNG energy share in the fuel charge, keeping the pilot diesel oil dose constant. The diesel oil dose was regulated by proper accelerator pedal deflection (setting the resistance value at the input to the common rail controller. The value of diesel oil energy dose was controlled by the torque value (engine load) and fuel consumption per second. Tests were carried out at the speed of 2000 rpm (speed of maximum torque) and for three pilot diesel oil doses that initiated ignition. The engine loads were: T = 20 Nm (BMEP = 0.1 MPa, energy dose E_ON = 36 kJ/s), T = 40 Nm (BMEP = 0.21 MPa, energy dose E_ON = 43 kJ/s) and T = 100 Nm (BMEP = 0.52 MPa, energy dose E_ON = 66 kJ/s). CNG quantity delivered into the cylinder was increased up to a distinct increase of noise emitted by the engine being a result of "hard" combustion or knock).

Changes of the engine load, resulted from changes of diesel oil and CNG energy doses, are presented in Fig. 5. The area of normal engine operation is marked lightly grey and the area of loads likely to achieve by the engine is marked dark grey. Maximum torque, that may be obtained at such type of fuelling is T = 220 Nm (BMEP = 1.13 MPa). Further increase of CNG energy share in the fuel charge resulted in "hard" combustion and knock.

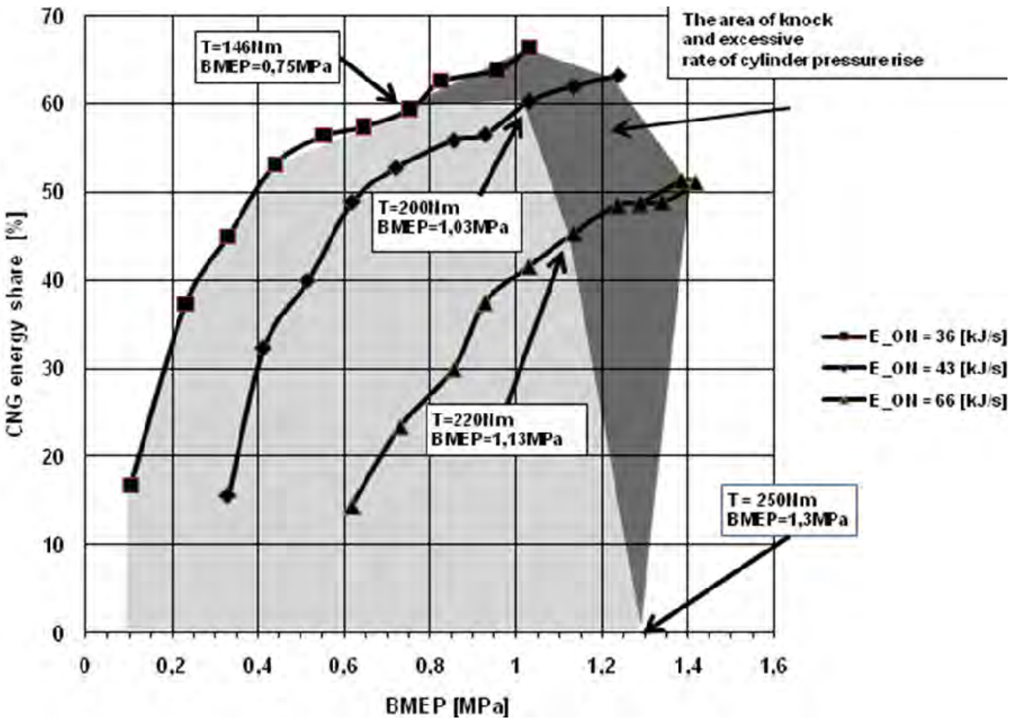

Fig. 5. Range of engine operation at dual fuelling. Engine speed N = 2000 rpm

Pressure runs presented in Fig. 6a, 6b and 6c were registered at operating points corresponding to maximum loads obtained at dual fuelling with the above mentioned pilot diesel oil doses that initiated ignition. Values of maximum pressures, in all analysed cases, were about 10 MPa (comparable with standard fuelling) or slightly lower.

In result of application of the factory common rail controller, maximum transient rates of pressure rise (dp/dφ)max do not exceed values of 0,35 MPa/C.A., therefore, they are within the range regarded as normal engine operation [5] and are comparable with those registered at standard fuelling.

As it was mentioned above, the result of an excessive increase of CNG energy share in the fuel charge is sudden increase of maximum operating pressures (above 10 MPa) and rate of pressure rise ($dp/d\varphi_{max}$ > 0.6 MPa/°C.A.). It manifested itself in increased engine noise.

Increased engine noise may be caused by high-frequency (about 7 kHz) engine head vibrations resulted from pressure pulsations or high rate of pressure rise (Fig. 6d and 7d).

Engine head vibrations and runs of heat release for three above mentioned diesel oil energy doses are presented in Fig. 7a, 7b and 7c. Similarly as in the case of standard fuelling, the heat is being released without a distinct phase of kinetic combustion. Engine head vibration amplitude during combustion does not exceed the value of 4.5 V.

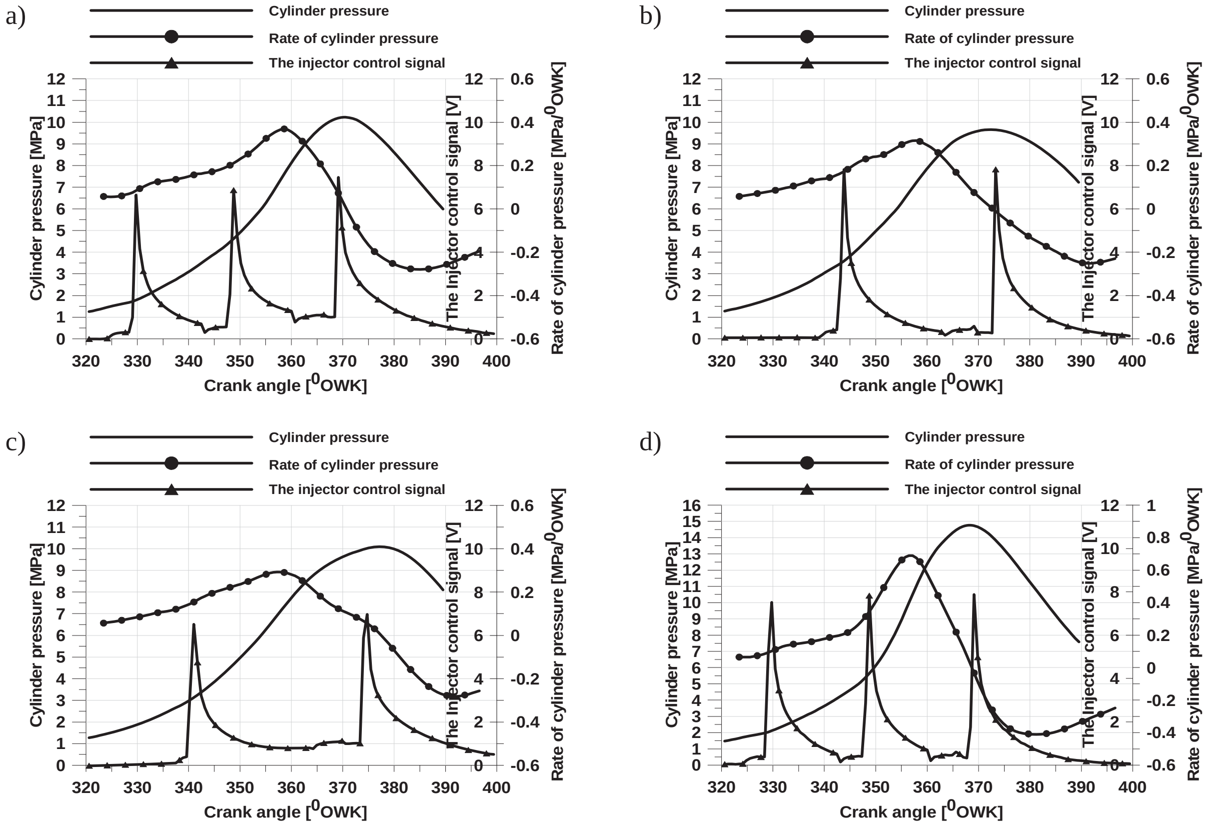

Fig. 6. Cylinder pressure changes, rate of cylinder pressure rise and voltage signal that controls the injector at maximum load an the speed of 2000 rpm for diesel oil energy dose: a) E_ON = 36 kJ/s, b) E_ON = 43 kJ/s, c) E_ON = 66 kJ/s, d) diesel oil energy dose E_ON = 36 kJ/s and maximum participation CNG

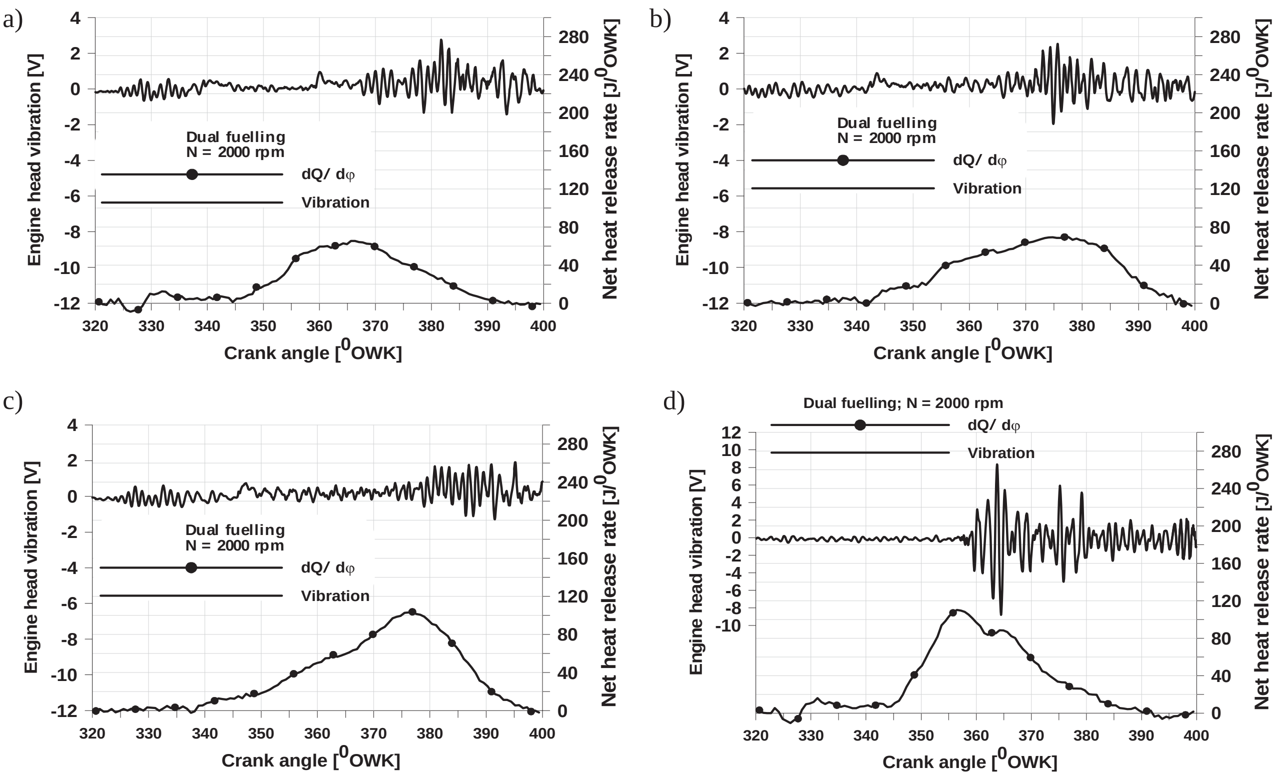

Fig. 7. Heat release and voltage signal amplitude from the knock sensor at the maximum load and engine speed 2000 rpm for diesel oil energy dose: a) E_ON = 36 kJ/s, b) E_ON = 43 kJ/s, c) E_ON = 66 kJ/s, d) E_ON = 36 kJ/s and maximum CNG share

5. Conclusions

The carried out research work and analysis of the obtained results allow formulating the following conclusions:

- dual fuelling with diesel oil (by common rail system) and CNG (indirect injection into the intake manifold) allows to obtaining loads lower y about 15% in comparison with standard fuelling,
- the main factors that limit an increase of CNG energy share in the fuel charge are excessive increase of maximum cylinder pressure (Pmax ≈ 15 MPa) and increase of the rate of pressure rise what manifests itself in "hard" engine operation that switches to knock (0.7 MPa/C.A.),
- maximum CNG energy share in the fuel charge delivered into the cylinder was about 60% at the diesel oil energy value equal to 36 kJ/s.

References

[1] Kowalewicz, A., Wojtyniak, M., *Natural gas a Fuel for Dual-Fuel Automotive Engines. A Review*, Archivum Combustionis, Vol. 29, No. 1-2, 2009.

[2] Zabłocki, M., *Dwupaliwowe silniki z zap łonem samoczynnym nap ędzane paliwem ciek łym i gazowym*, Seria Nowa Technika. Zeszyt 80, WNT, Warszawa 1969.

[3] Kowalewicz, A., Pawlak, G., Wołoszyn, R., Różycki, A., Duchniak, P., *Adaptacja turbo-doładowanego silnika do dwupaliwowego zasilania gazem ziemnym i olejem nap ędowym*, Projekt badawczy, Nr 4T12D00230.

[4] Różycki, A., *Microcomputer system for measurement of high speed parameters for IC engines*, Bratislava 2001 8th EAEC Congress, paper n° SAITS 01196, Bratislava 2001.

[5] Wajand, J. A., *Silniki o zapłonie samoczynnym*, WNT, Warszawa 1980.