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EVALUATING COMBUSTION, PERFORMANCE AND EMISSION CHARACTERISTICS OF CI ENGINE OPERATING ON DIESEL FUEL ENRICHED WITH HHO GAS

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Abstract

Research of efficient and ecological parameters was carried out with compression ignition (CI) engine using diesel fuel and additionally supplied hydrogen and oxygen (HHO) gas mixture. HHO gas is produced by electrolysis when the water was dissociating. At constant engine's brake torque and with increasing HHO gas volumetric concentration in taken air up to 0.2%, engine efficient indicators varies marginally, however, with bigger HHO concentration these parameters becomes worse. HHO increases smokiness, but it decreases NOx concentration in exhaust gas. Numerical analysis of combustion process using AVL BOOST software lets to conclude that hydrogen, which is found in HHO gas, ignites faster than diesel fuel and air mixture. Hydrogen combustion before TDC makes a negative work and it changes diesel fuel combustion process – diesel ignition delay phase becomes shorter, kinetic (premixed) combustion phase intensity gets smaller.

Keywords: *CI engine, HHO gas, engine efficiency, emission*

1. Introduction

In course of depletion of the natural fuel resources, growth of their prices and the increase of environmental pollution, it is strived to improve internal combustion engines, in particular in the aspect of fuel consumption and emission of pollutants [8, 20. In recent years, an attention was focused on the benefits of alternative fuels in improvement of the above-mentioned indicators. The key pollutants caused by usual hydrocarbon fuels include unburnt and partially burnt hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_x) and harmful particulate matter (PM) [10, 13, 20, 24]. Higher diesel engine efficiency is advantageous because of reduced fuel consumption; in addition, the problem of "greenhouse effect" is tackled [10, 13, 20, 24].

An increase of using an alternative energy source (hydrogen) is encouraged by „Europe 2020" programme that develops the guidelines for broad using the alternative fuels in Europe. Hydrogen distinguishes itself for specific properties, as compared to hydrocarbon fuels; in addition, this fuel does not contain carbon [11, 21, 25, 33, 39]. Mostly applicable method of hydrogen production is water electrolysis because of unrestricted resources of the raw material and simple technology of production [11, 25, 33]. However, hydrogen using in a vehicle causes abundant problems, such as hydrogen feeding facilities, safety, and its storage in the vehicle [11, 14, 21, 40. Very low density of hydrogen, high pressure of its storage in a vehicle (~70 MPa) and high permeability require large and particularly tight reservoirs (made of special steel or composite materials) for keeping hydrogen in a vehicle [7, 11, 40]. One of the ways for tackling the said problems is production of hydrogen in the vehicle.

If hydrogen is used as an additive in internal combustion engines, C/H ratio decreases and causes reduction of CO_2 emission; in addition, the fuel combustion rate and the quality of combustion is repetition; the toxicity of the exhaust gas is reduced in order to reduction of unburnt hydrocarbons and carbon monoxide (CO) in the exhaust gas as well as reduction of its smokiness; however, NO_x

emission grows [5, 9, 26, 29, 30, 35, 38]. Chaisermtawan et al. [3] applied thermodynamic modelling methods for investigation of supplemental influence of thermodynamic properties of hydrogen on operation of diesel engines using lean mixture, the combustion parameters, and emission of hydrogen emission. Jarungthammachote et al. [16] performed thermodynamic modelling of diesel engine operation cycle by changing the contents of H_2. The results show that growing of H_2 concentration causes an increase of the cylinder pressure and temperature, thus resulting an increase of NO_x emission. To reduce NO_x emission on increased H_2 feeding, the exhaust gas recirculation (EGR) should be increased. It was confirmed by the research works of Heffel [12]. Hydrogen fed to the engine heats up, expands, and occupies a part of the cylinder volume, so less quantity of air gets into it and the power of the engine reduces [25]. Various scientists in their research works found different influences of hydrogen on energy efficiency of the engine [1, 5, 6, 9, 19, 22, 26, 29, 30, 33].

The goal of the investigation: to establish the peculiarities of different amounts of the mixture of H_2 and O_2 gases (HHO) in CI engine and its influence on the energy and environmental performance of the engine operating on diesel fuel.

2. Properties of the hydrogen fuel

The limits of ignition of hydrogen-air mixture are very broad, as compared to diesel fuel (Tab. 1). Taking into account the said property it may be stated that hydrogen may be combusted in an internal combustion engine at various fuel-air mixture ratios. The principal advantage is that using lean mixtures results in considerable saving of fuel and improving the combustion reaction. In addition, the peak temperature of combustion is lower, so the content of nitrogen oxides in the exhaust gas is lower. Hydrogen ignition requires about seventeen times less energy consumption (0.017 mJ), as compared to petrol (0.29 mJ) [11]. This property enables igniting very lean hydrogen-air mixtures in an internal combustion engine and ensuring a rapid combustion. Unfortunately, the low energy consumption required for ignition may cause a problem of advanced ignition of hydrogen [4, 15, 18, 28, 34].

Tab. 1. The principal properties of hydrogen and traditional fuels [11, 20, 33]

Physical and chemical properties	Hydrogen	Diesel fuel (D)
Chemical formula	H_2	C_9-C_{25}
Lower heating value, H_L, MJ/kg	120	42.5
Density, ρ, kg/m^3 at 0°C and 0.1 MPa	~0.09	~850
Viscosity at 40°C (mm^2/s)	-	~3.5
Relative density with respect to air	~0.0695	~654
Mass content of principal elements, %	100 H	84-87 C, 13-16 H
Molecular weight	2	200-300
Boiling temperature, °C	-253	180–360
Freezing temperature, °C	-260	-34
Specific vaporization heat, kJ/kg	~120	~250
Auto-ignition temperature, °C	560-585	180-320
Auto-ignition energy, mJ	0.017	-
Laminar flame spreading speed, m/s	~2.7	-
Flame temperature, °C	2207	2327
Cetane number	5-10	~53
Octane number (by the method under research)	130	30
Air required for combustion of 1 kg of the substance, kg/kg	34.5	~14.6
Possible limits of auto-ignition of the combustible mixture, λ	0.14-9.85	0.82-12
Explosive limits, vol. % in air	4-77	0.6-7.5
Diffusion coefficient, cm^2/s	0.63	-

Ignition of the hydrogen-air mixture in the cylinder may be caused by hot gases or hot particles from the walls of the cylinder. They can cause an auto-ignition at an undesirable moment [4]. A settlement of the said problem would enable a broader application of hydrogen in internal combustion engines. The problem of undesirable auto-ignition may be tackled by applying the methods of combustible mixture dilution, for example, by EGR or by adding an inert gas, such as helium, nitrogen and so on, to the combustible mixture, or water injection [27].

It is stated that, decomposition of water by electrolysis a part of hydrogen and oxygen molecules (HHO gas) on production of gas form monoatomic structures (single-atom molecules) [15, 28] and the auto-ignition temperature of such combustible mixture is lower, as compared to hydrogen (that structure is diatomic). Because of this, HHO gas mixture does not require an external source of ignition, such as a spark plug or an electric spark.

When HHO mixture ignites, an explosion (extension) and implosion (contraction) of the combustible mixture take place and result in production of H_2O; and the energy of reaction is released as thermal energy. In case of single-atom molecules, no interatomic bonds should be destructed prior to the repeated production of H_2O. Therefore, the energy level of HHO gas is higher. On HHO combustion, H_2O is produced; it gets into collision with the fuel and they unite. H_2O turns into a core and fuel turns into its shell (because of different densities of them). During the compression stroke, the pressure and temperature grow, H_2O transforms into vapour, and the fuel is decomposed [15].

3. HHO gas production by electrolysis

A mixture of hydrogen and oxygen is produced on water decomposition by electrolysis. At pressure of 0.1 MPa and temperature of 25°C, the process of electrolyse requires the difference of potentials between the anode and cathode to be equal to 1.23 V [11]. If a solution of potassium hydroxide (KOH) electrolyte is used, the voltage between the electrodes may achieves 2.0-2.5 V, when the current density is 2000 A/m^2 at the temperature of electrolyte equal to 80°C [31]. In absence of an OH^-ion conductive membrane between the anode and the cathode, the hydrogen and oxygen ions blend and a mixture of H_2 and O_2 gases (HHO) with volumetric hydrogen/oxygen ratio 2 : 1 is formed.

From 1 kg of water (upon electric power consumption 22.9 MJ), ~1860 litre of HHO gas where the contents of H_2 is ~1240 litre and the content of O_2 is ~620 litre is produced. At the pressure p = 0.1 MPa and the temperature T = 0°C, the density of oxygen gas ρ_{O_2} = 1.43 kg/m^3, the density of hydrogen ρ_{H_2} = 0.09 kg/m^3, and the density of HHO gas mixture ρ_{HHO} = 0.54 kg/m^3. One litre of HHO gas included 0.666 litre of H_2 gas with mass $m_{H_2/l}$ = 0.06 g and 0.333 litre O_2 gas with mass $m_{O_2/l}$ = 0.48 g.

4. Research methodology

Diesel engine 1.9 TDI (1Z type) with electronic controlled BOSCH VP37 distribution type fuel pump and turbocharger was used for the tests. Exhaust gas recirculation (EGR) system was activated during the tests. Tests were carried out at engine speed – n = 2000 rpm. Brake torque (M_B) load was 45 Nm. Scheme of laboratory equipment is shown in Fig. 1. Engine brake stand KI-5543 was used for the load M_B and crankshaft speed determination. Torque measurement error was ±1.23 Nm. Hourly fuel consumption B_f was measured by electronic scales SK-5000 and stopwatch, accuracy of B_f determination was 0.5%. Pollutants in exhaust gas were measured using gas analysers AVL DICOM 4000 (for CO, CO_2, HC, NO_x) and AVL DiSmoke (for Absorption coefficient k-Value).

In-cylinder pressure p was recorded by a piezo sensor GG2-1569 which is integrated in the preheating plug and was recorded using AVL DiTEST DPM 800 equipment with accuracy of 1%.

Intake air mass flow meter measured by BOSCH HFM 5 with accuracy of 2%. Intake manifold pressure measured with pressure gauge Delta OHM HD 2304.0. Sensor of device TP704-2BAI mounted ahead of intake manifold with an error of ±0.0002 MPa. Exhaust and intake gases temperature meter – K-type thermocouple (accuracy ± 1.5°C) was used.

For production the mixture of H_2 and O_2 gases, the water electrolysis equipment was used. The electrolyte consisted of 96% H_2O and 4% KOH. For HHO gas production used direct current (DC), which is obtained from additional energy source. Flow rates are regulated by current with current modulator in order to obtain required mixture of H_2 and O_2 gases. Other researchers [22, 19] use similar HHO supply systems. Electric power consumptions, which are ~220 W/ (l/min), were determined by additional experiments.

Figure 2 shows the influence of HHO gas on the lower heating value of fuel, when the engine operates on diesel fuel and the volume of HHO gas is increased from 0 l/min to 3 l/min. The results of the calculations show an increase of the heating value of the mixture of diesel fuel and H_2 from 42.5 MJ/kg to 42.79 MJ/kg (0.68%).

The synthesis of the combustion process of the tested engine was performed by modelling the said process upon applying AVL BOOST programme. In the programme, the two-zone combustion model was used [32]. Taking into account the parameters of the investigated fuel, an open thermodynamic system that exchange the mass and energy with other systems of the engine is analysed. This enables forming a model of an operation cycle as a submodule of other processes, such as gas exchange processes; compression processes; combustion and expansion processes.

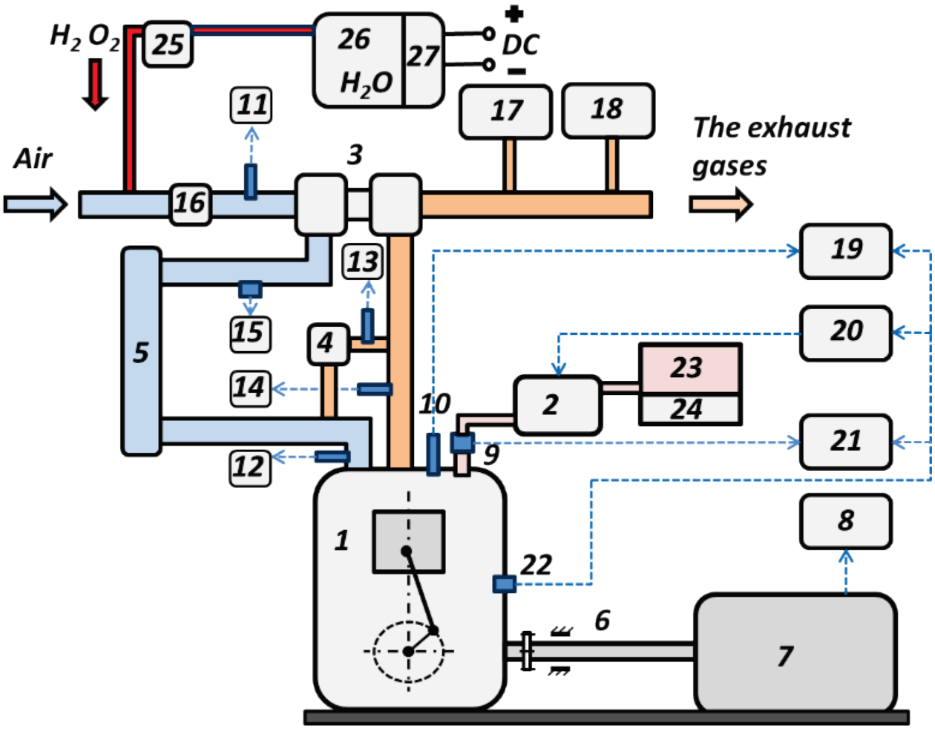

Fig. 1. The scheme of engine testing equipment: 1 – 1.9 TDI engine; 2 – high pressure fuel pump; 3 – turbocharger 4 – EGR valve; 5 – air cooler; 6 – connecting shaft; 7 – engine load plate; 8 – engine torque and rotational speed recording equipment; 9 – fuel injection timing sensor; 10 – cylinder pressure sensor; 11 – intake air temperature sensor; 12 – intake gas temperature meter; 13 – recirculated exhaust gas (EGR) temperature sensor; 14 – exhaust gas temperature meter; 15 – air pressure meter; 16 – air mass meter; 17 – exhaust gas analyser; 18 – smoke analyser 19 – cylinder pressure recording equipment; 20 – fuel injection moment control equipment; 21 – fuel injection moment recording equipment; 22 – crankshaft position sensor; 23 – fuel tank; 24 – fuel consumption calculation equipment; 25 – flame arrestor; 26 – HHO gas generator; 27 – HHO gas flow controller

The rate of heat release (*ROHR*) during an operation cycle is found upon applying the heat release function [37]:

$$\frac{dx}{d\varphi} = 6.908 \frac{m_v + 1}{\varphi_C} \left(\frac{\varphi}{\varphi_C} \right)^{m_v} \exp \left[-6.908 \left(\frac{\varphi}{\varphi_C} \right)^{m_v + 1} \right], \tag{1}$$

$$dx = \frac{dQ}{Q}. \tag{2}$$

where:
Q – the heat release by the fuel per operation cycle, J,
φ – crankshaft turning angle, °CA,
m_v – Vibe‘s combustion parameter,
φ_C – combustion duration, °CA.

When the operational parameters of the engine (the cylinder pressure during an operation cycle, fuel and air consumption) are additionally entered BURN (a subprogram of AVL BOOST), the start of combustion φ_0 in the engine cylinder, its duration φ_C and Vibe‘s combustion parameter m_v are found.

5. Results and their analysis

At an engine speed n = 2000 rpm, when the engine is loaded with M_B = 45 Nm and increasing HHO gas amount up to 3 l/min, HHO gas volumetric concentration in the engine air intake ($C_{\_V\_HHO}$) grows up to ~0.24% (Fig. 3). The mass concentration of hydrogen in HHO gas included in the combustible diesel and H_2 mixture ($C_{\_m\_H2}$) grows up to ~0.38%, so the concentration of hydrogen energy in the mixture of fuel ($C_{\_E\_H2}$) grows up to ~1.06%.

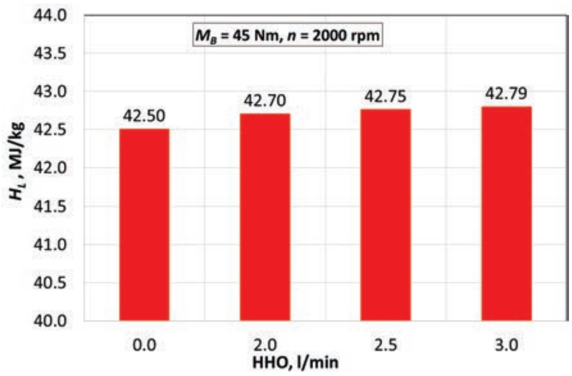

Fig. 2. The influence of HHO gas on the lower heat value of the mixture of fuels

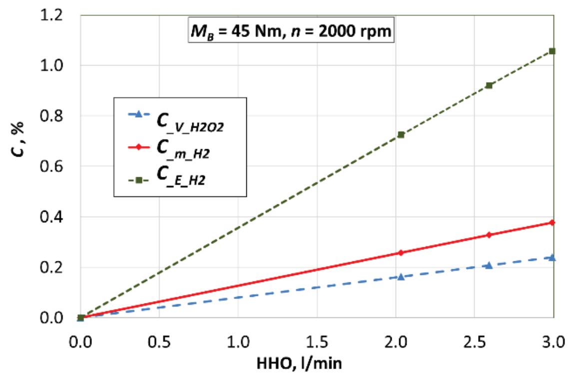

Fig. 3. The change of HHO gas volumetric concentration $C_{\_V\_HHO}$, the mass concentration of hydrogen $C_{\_m\_H2}$, and the concentration of hydrogen energy in the mixture of fuel $C_{\_E\_H2}$

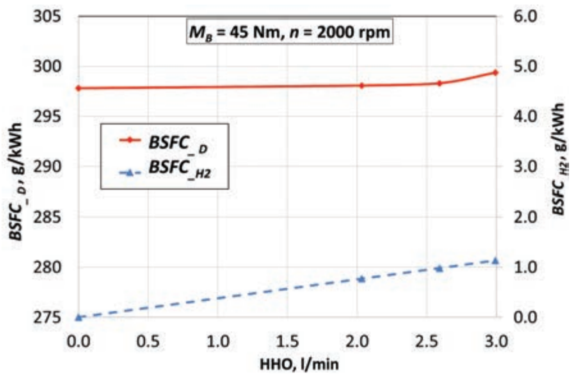

Fig. 4. HHO gas amount influence for Break Specific Fuel Consumption (BSFC)

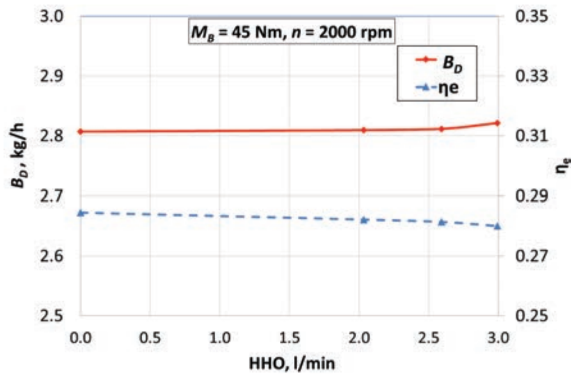

Fig. 5. HHO gas amount influence for hourly fuel consumption (B_D) ir engine efficiency (η_e)

The Break Specific Fuel (diesel) Consumption (*BSFCD*) (Fig. 4) and hourly diesel fuel consumptions B_D (Fig. 5) increase fractionally (~0.15%), when increasing HHO gas amount up to 2.5 l/min ($C_{\_V\_HHO}$ 0.2%). However, increase of HHO gas up to 3.0 l/min ($C_{\_V\_HHO}$ 0.24%) showed diesel fuel consumption increase ~0.5%. Break Specific Fuel (hydrogen) Consumption ($BSFCH_2$) reach 1.13 g/kWh level when 3.0 l/min of HHO gas is used. The fixed increases of diesel fuel consumption can be caused by auto-ignition of active monoatomic hydrogen in HHO gas [15, 28] and its partial combustion takes place before the piston achieves TDC. The auto-ignition of hydrogen in compressed air (when the temperature is lower than auto-ignition temperature – ~833K) theoretically described in [17].

The assessment of diesel and hydrogen consumptions revealed that increase of HHO gas amount up to 2.5 l/min, influence engine efficiency, which decrease from 0.284 to 0.281 (~1.1%). $_e$ decrease to 0.280 (~1.4%) (Fig. 5) when HHO gas is increased up to 3.0 l/min. These results are contrary to other researchers' results; where it is declared that HHO gas addition improve compression ignition engine efficiency [5, 9, 22, 38].

The increase of HHO gas up to 3 l/min decreased NO_x concentration from 161 ppm to 156 ppm (~3%) in exhaust gas (Fig. 6). However, fuel consumptions increased when holding constant M_B = 45 Nm engine load. This can be explained by hydrogen auto-ignition before TDC (before start of diesel injection), which makes shorter fuel ignition delay phase and makes smaller intensity of kinetic (premixed) combustion phase and NO_x emissions. Shorter ignition delay phase, when hydrogen supplied additionally, was observed in other researches [2, 6]. However, the smokiness (Absorption coefficient k-Value) increase from 0.338 m^{-1} to 0.347 m^{-1} (~3%), because HHO gas works as negative work and increase fuel consumption, also decrease excess air ratio coefficient.

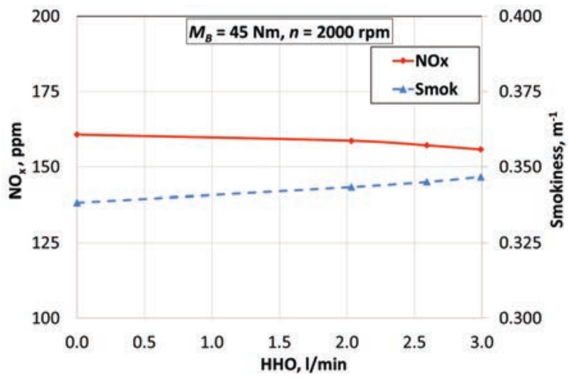

Fig. 6. HHO gas amount influence for NO_x concentration and smokiness

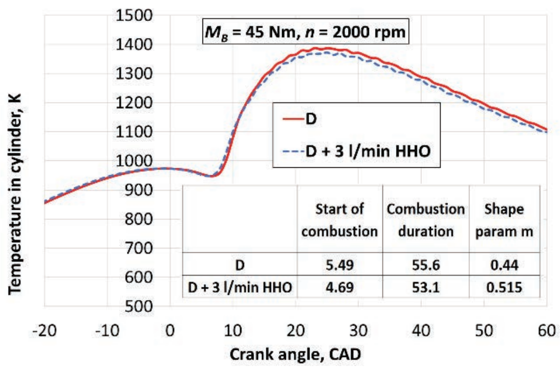

Fig. 7. Combustion process indicators and temperature in cylinder

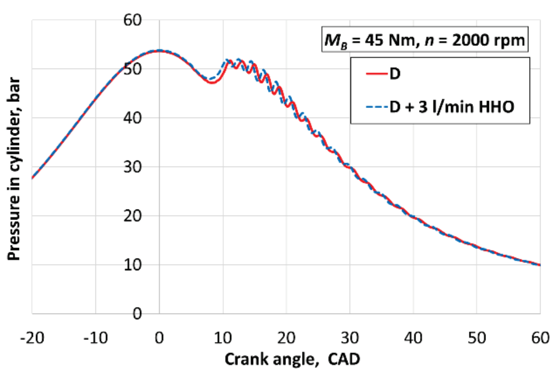

Fig. 8. Pressure variation in cylinder

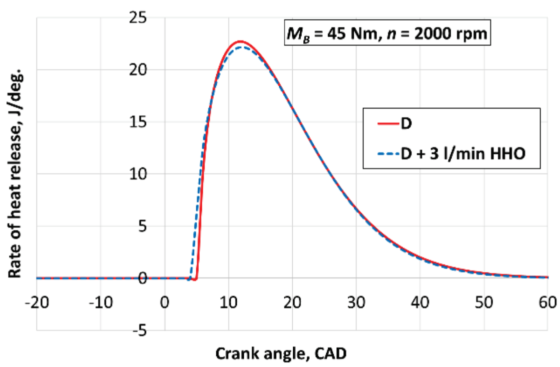

Fig. 9. Heat release in cylinder

The analysis of combustion process, using AVL BOOST software, revealed that fuel ignition delay phase becomes shorter ~0.8° of crank angle due to additional supply of HHO gas. The start of combustion changed from 5.49° to 6.69° crank angle (Fig. 7). Vibe's combustion parameter *m* changed from 0.44 to 0.515. It was also determined that temperature of compressed gas before TDC increase 4.7 K and pressure increase 0.16 bar due to additional HHO gas use (Fig. 8). Such finding lets to confirm the affirmation that hydrogen, which is in HHO gas, ignites before piston reaches TDC. The rate of heat release (*ROHR*) character (Fig. 9) changed due to higher temperature and pressure in cylinder – kinetic (premixed) combustion phase intensity declined which explains NO_x emission decrease. Lower *ROHR* intensity is confirmed by Uludamar et al. [36] researches, where HHO addition (from 2 l/min to 6 l/min) decreased engine vibrations.

6. Conclusions

Research conclusions of compression ignition engine, working with diesel fuel and additionally supplied variable hydrogen and oxygen (HHO) gas mixture amounts, are such:

1. Hourly and Break Specific Diesel Consumption increase little when increasing HHO gas concentration in the engine intake air up to ~0.2%. However, engine fuel consumptions increase (~0.5%) and efficiency decrease (~1.4%) when HHO gas concentration is increased more (up to ~0.24%).
2. NO_x concentration in exhaust gas decrease ~3%, but smokiness increases 3%, when HHO gas concentration is increased up to ~0.24%.
3. The increase of fuel consumption and smokiness, when HHO gas is additionally supplied, can be explained by hydrogen auto-ignition due to high temperature of compressed gas. Hydrogen makes negative work when ignites before TDC.
4. When the diesel is injected, fuel has shorter ignition delay phase due to increased pressure and temperature before TDC in the cylinder. The kinetic (premixed) combustion phase intensity decline, which explains lower NO_x concentration in exhaust gas. Such phenomena can be clearer when HHO concentration is increased.

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