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THE INFLUENCE OF OXYGEN DISSOLVED IN THE DIESEL FUEL ON THE COMBUSTION PROCESS AND MUTUAL CORELATION BETWEEN NITROGEN OXIDE AND EXHAUST GAS OPACITY

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Abstract

The paper presents a concept of improving the injection and spraying processes with the use of the oxygen dissolved in the diesel fuel and the results of experimental investigations carried out in order to verify it.
The combustion process of the direct injection compression-ignition engine being normally performed at a high excess of combustion air factor for the whole engine operation range is affected by local deficiencies of oxygen inside the fuel sprays in a combustion chamber. This fact is one of the main reasons for forming the harmful compounds in exhaust gases such as NO_x *and PM.*
The aim of the presented concept is to improve the fuel spray atomization by the release of the oxygen previously dissolved in the fuel. The influence of dissolving the oxygen in the diesel fuel on the run of the combustion process and concentration toxic compounds in exhaust gas has been presented in the paper.

Keywords: *spraying processes, combustion process, emission, fuel solution*

1. Introduction

The specificity of the combustion process being realized in the direct injection compression ignition engine (CI) consist in a fact that the liquid fuel in a form of fuel sprays is supplied to the engine combustion chamber right before the piston top dead centre (TDC). Thus a complete process of preparing the mixture for being burnt, i.e. a disintegration of the fuel spray into drops, their evaporation and mixing with air needs to be performed in a very short time. For such a way of fuelling the engine some local and very significant differences of the excess air factor values λ are met (fig. 1). The values met in the combustion chamber range from the infinite high one in the area which is not covered by the fuel spray, throughout $\lambda \approx 0.8 \div 1.5$ at the edges of the fuel spray initializing the ignition to $\lambda \approx 0$ being recorded in the spray core. The local deficiencies of oxygen occur despite the high value of the global excess of air the value of which changes with the engine load and ranges from $\lambda \approx 11$ at the engine idle running to $\lambda \approx 1.4 \div 1.3$ at the engine full load, i.e. for the operating conditions corresponding to the outer engine operating characteristic.

In case of the combustion process the local deficiencies of oxygen are one of the most important reasons for forming carbon oxides, hydrocarbons, and partly of forming the particulate matter, whereas the formation of nitrogen oxides is mainly connected with the kinetics of developing the flame which generates the value of the produced heat as the heat delivery speed determines the level of temperature in a combustion chamber. All of it causes that the fuel spraying, in addition to the air swirl, is of the decisive importance for preparing the mixture. The quality of spraying is determined by two basic physical factors: the pressure existing in the nozzle area right before the nozzle whole and the pressure in the combustion chamber where the fuel spray is directed to. An increase in the injection pressure values improves the fuel spraying and it is a current preferred tendency of the developments of the injection systems for the CI engines. The changes which are done in the Common Rail (CR) system confirm the above statement. Every next generation of this system is characterized by the injection pressure values that are higher that ones of the previously generation.

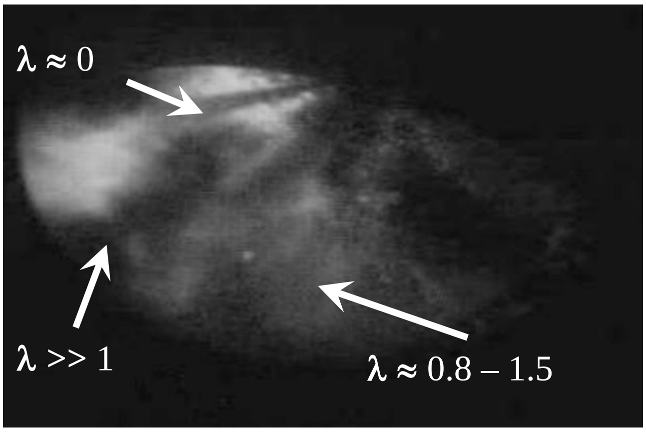

Fig. 1. The combustion process in the combustion chamber of a direct injection compression ignition engine

The improvement of the fuel spraying can be achieved not only by increasing the injection pressure but also by modifications to the mechanism causing the disintegration of the fuel spray. The velocity of the fuel outflow from the nozzle is a single physical stimulus which causes the disintegration of fuel spray in the currently used mechanism of spraying. In order to achieve the improvement of spraying it is proposed to use in the discussed mechanism an additional physical stimulus resulting from the physical properties of the gas-in liquid solution [1, 2, 5, 6]. The amount of gas that can be dissolved in a liquid significantly depends on the pressure. A spontaneous release of gas at the non-equilibrium state caused by the pressure fuel is very characteristic for such a solution. The process of releasing the gas from a liquid is of a volumetric nature, i.e. the gas is being released simultaneously from the whole liquid volume. The energetic effects which accompany that process depend on the speed of the stimulus modifications and the gas which is released always presents a tendency to break the bonds of liquid molecules. Under such conditions the state of liquid is similar to that state of boiling. The presented properties of a liquid are very desirable in the injection system of the diesel engine. Thus a concept of using the effect accompanying the process of releasing the gas from a liquid for improving the existing mechanism of fuel oil spraying has been developed.

This concept consists in adding the appropriate amount of air to the fuel, its dissolving under high pressure conditions (in a high pressure pump) and keeping it in a form of solution in a high-pressure section of the engine supply system (up to the nozzle) until the moment of injection, occurs as shown in fig. 2. In this case the assumed injection pressure determines the energetic solution level at which the equilibrium state is achieved.

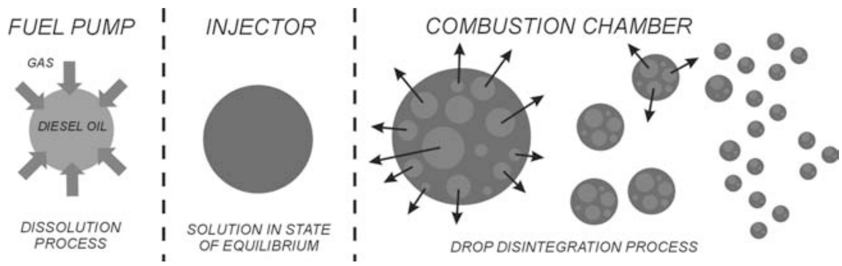

Fig. 2. The illustration of a concept of the spraying improvement by gas dissolved in fuel [1]

The use of the effect accompanying the process of releasing the air dissolved in the fuel oil occurs in the combustion chamber area when, due to a sudden pressure drop a serious disturbance of an equilibrium state occurs in a solution. The pressure drop from the injection pressure level to the pressure level existing in the surroundings of the fuel stream occurs at the moment of the injection beginning. A detailed description of this concept is presented in [1].

2. Test stand

The tests were carried out on the engine test stand equipped with the direct injection compression-ignition test engine AVL 5804. This is an one-cylinder engine equipped with a four-valve cylinder head and two camshafts. The injector is situated in the cylinder head centrally in the cylinder axis. The engine was equipped with a conceptual supply system of a Common Rail type controlled by a SesubCR system – i.e. a system specially developed for electronic controlling the Common Rail unit. The test stand was equipped with a brake provided for realization of the set value of the engine crankshaft speed regardless of the engine load. The test stand also included the lubricating oil and cooling fluid temperature stabilization systems.

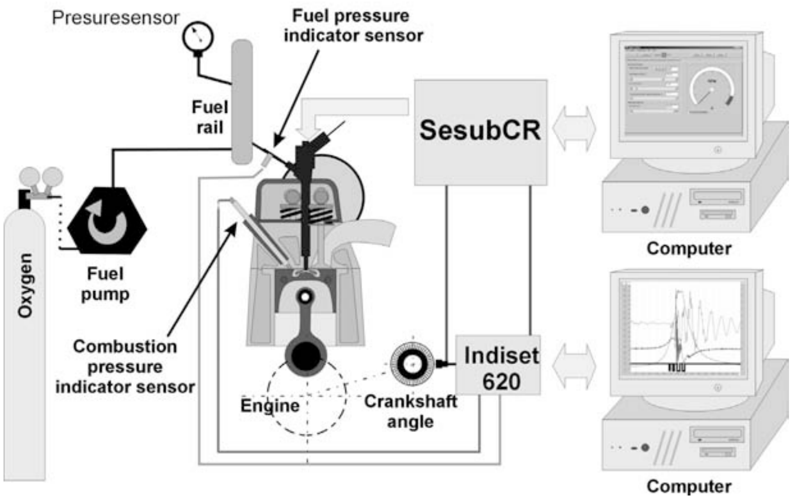

Fig. 3. The test stand

The fuel was supplied to the engine by an accumulator supply system including a supply pump with an independent drive unit. The fuel compressed in the pump was pumped (forced) to an accumulator (a container) called a pressure accumulator from which it was delivered to the BOSCH 0445 110 131 injector. Its work was controlled by the SesubCR system. The relevant injection parameters i.e. the injection commencement angle and injection duration time were set by a computer using a program for the SesubCR system. In order to perform a correct analysis of the changes in the engine operation parameters it was necessary to complete the information on the cylinder pressure characteristics, the cylinder pressure characteristics just before the injector and also on the characteristics of the pulses controlling the injector operation as a function of the crank angle. For those reasons the engine was equipped with a piezoelectric sensor of the indicated pressure situated in the engine cylinder head just before the injector directly on the injection pipe connecting the injector with the accumulator. The voltage pulses generated by those sensors, after their amplification, and the signal from pulses controlling the work of the injector as well, were sent to the Indiset 620 system provided for recording the quick changing engine processes given in the voltage form. For the comparative nature of the performed examinations it was necessary to use two supply pumps, the conventional one, which compresses the diesel oil only, and the second one which makes the gas-in-fuel dissolving possible while it is being pumped (forced) (fig. 4).

During the examinations the tonnage oxygen taken out from the high pressure oxygen cylinder with use of the pressure reducing valve was used as a gas to be dissolved in fuel. Oxygen at the pressure value of 1 bar was supplied to the forcing section area of the pump through a non-return valve during the piston moving downwards (fig. 4a). As soon as the piston reveals the lower passage the gas supplying valve closes and the diesel oil supplying to the fuel forcing section starts (fig. 4b). As soon as the piston moving upwards closes the passage supplying the fuel the compression of the oxygen and diesel oil in the forcing section starts, during which a gas-in-oil dissolving process occurs. The liquid solution obtained in this way is pumped (forced) to the fuel accumulator (fig. 4c). From the fuel accumulator it is supplied to the injector, and next to the combustion chamber of the DI engine. Considering the specificity of examinations the relevant methodology of their performing had to be developed.

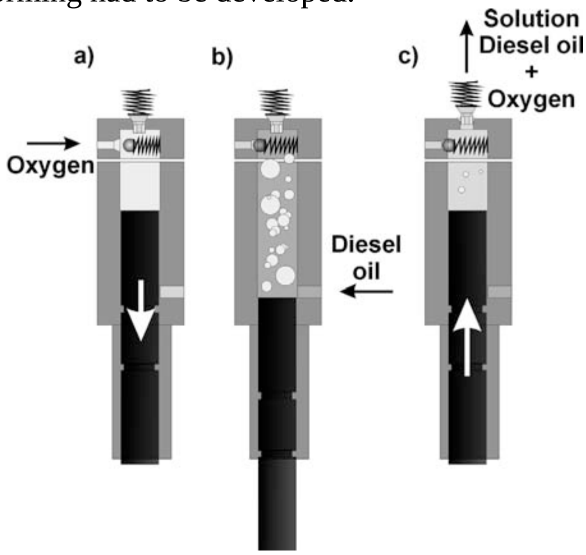

Fig. 4. The realization of the gas-in-diesel oil dissolving process

3. Examination procedure

The examination was of a comparative nature so it was carried out in two stages. In the first stage the engine was fuelled with diesel oil and the injection parameters were set as follows:
- the simulated engine speed : 2000 rpm;
- the fuel pressure in rail: 40 MPa;
- the duration time of electric pulse opening the injector: 0.55; 0.65; 0.75; 0.87; 0.98 ms.

In the second research stage the engine was fuelled with diesel oil -and-dissolved oxygen at the same settings of the above injection parameters and the oxygen pressure value in pump: 1 bar.
During the examinations some measurements of the toxic exhaust gas compounds were performed. In each of the set engine operating points the cylinder indicated pressure values, fuel in the injection pipe before the injector, and characteristics of the intensity of the injector opening current values were additionally measured. Those measurements allowed to estimate the similarity of the parameters of the fuel injection realized in each stage of the performed examinations. The obtained parameters were subject to the mutual comparative analysis.

4. Test results and discussion

The evaluation of the discussed conception will be made on the basis of the comparative analysis performed for two groups of values. The first group includes the cylinder pressure value and the rate of the cylinder pressure rise. These quantities are closely connected with the combustion process kinetics. The second group includes the basic components of exhaust gas, the emission of which is subject to the limitation. They are: nitrogen oxides NO_x, and exhaust gas smoke.

Having realized their research program the authors have gathered some very extensive comparative material which one cannot help fully presenting here. In this paper only some exemplary results are presented on a basis of which the tendencies of the influence of oxygen content in the fuel on the engine operation, that is observed in the whole research range, can be shown. These results are presented in a graphic form.

The nature of the influence of the release of oxygen dissolved in a fuel on the cylinder pressure Pc characteristic during the combustion process is shown on an example of a single point of work of the engine. This influence is presented directly on the pressure characteristic as shown in fig. 5. In this figure the characteristic of fuel pressure in the high pressure rail Pr and the characteristic of a signal t controlling the opening are additionally plotted. At introducing the fuel solution and increasing the mass of the oxygen dissolved in it a clear tendency to shorten compression-ignition delay appears. The character of changes values, as one emphasized in fig. 6, recurred for all examined engine operating conditions.

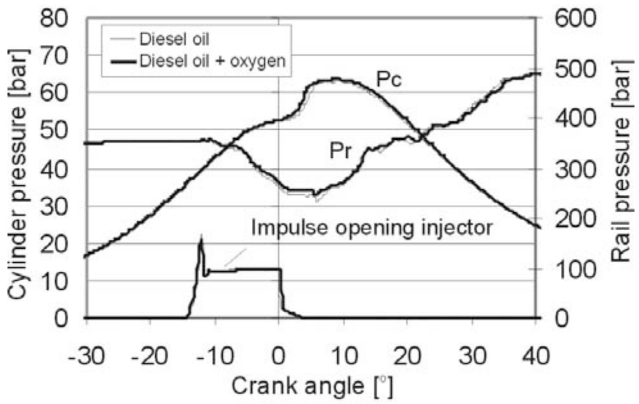

Fig. 5. Cylinder pressure of engine supply with diesel fuel and diesel fuel with dissolved oxygen;
n = 2000 rpm, Pw = 35 MPa, t = 1,21 ms

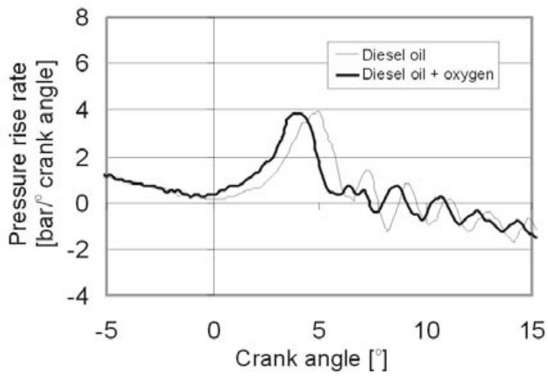

Fig. 6. Pressure rise rate as function of crank angle;
n = 2000 rpm, Pw = 35 MPa, t = 1,21 ms

The discussed character of changes is closely connected with the compression-ignition delay angle. After adding the oxygen to the fuel a compression ignition delay angle is subject to a significant shortening in comparison to one noted at supplying with fuel without oxygen. This shortening depends on the amount of the oxygen dissolved in a fuel and, what should be considered as obvious, on the location of the engine operation point on the general engine characteristic. Increasing the amount of the dissolved oxygen shortens the time of the compression ignition delay.

The decrease in the pressure rise rate which is distinctly seen in the combustion chamber should be also explained by a shortened compression ignition delay angle. The tendency of such association is also unambiguous: an increase in the amount of the dissolved oxygen results in the lower rate of the pressure rise. In case of delivering the oxygen under the pressure of 1 bar the maximum rate of the pressure rise was noticeable decreased.

The results of the toxic exhaust gas compound emission measurements obtained for the individual engine operation points during the fuelling the engine with diesel oil containing the dissolved oxygen were compared with the emission values obtained for the engine fuelled with a conventional diesel oil (table 1).

The relative changes in the concentration values obtained for the individual compounds are given in figure 7. The concentration values for the individual compounds in each operating point for the engine fuelled with the conventional diesel oil were assumed as a 100% concentration value for a given compound of the exhaust gas emission. The concentration values obtained for the engine fuelled with the diesel oil and dissolved oxygen were referred to that value.

Table 1. The concentration values for the selected exhaust gas components (engine speed 2000 rpm)

Fuel	Injection time [ms]	Nitrogen oxides [ppm]	Opacity [FSN]
1	2	3	4
Diesel oil	0.55	413	2.8
	0.65	500	4.1
	0.75	516	5.5
	0.87	531	7.2
	0.98	538	9.0
Diesel oil + Oxygen	0.55	546	2.0
	0.65	561	3.2
	0.75	598	4.2
	0.87	604	5.7
	0.98	559	8.2

Comparison of the obtained results allows to evaluate the effect of the oxygen dissolved in diesel oil on the changes in concentrations of the exhaust gas components. Some changes in the concentrations of nitrogen oxides were noticed. The increase in concentration of approx. 30% occurred at low load of the engine. Next, as the engine load increased that concentration decreased and it was of 5–17 %. However, it still was higher than the concentration measured for the engine fuelled with diesel oil. The opacity in exhaust gas decreased by 5–25 %.

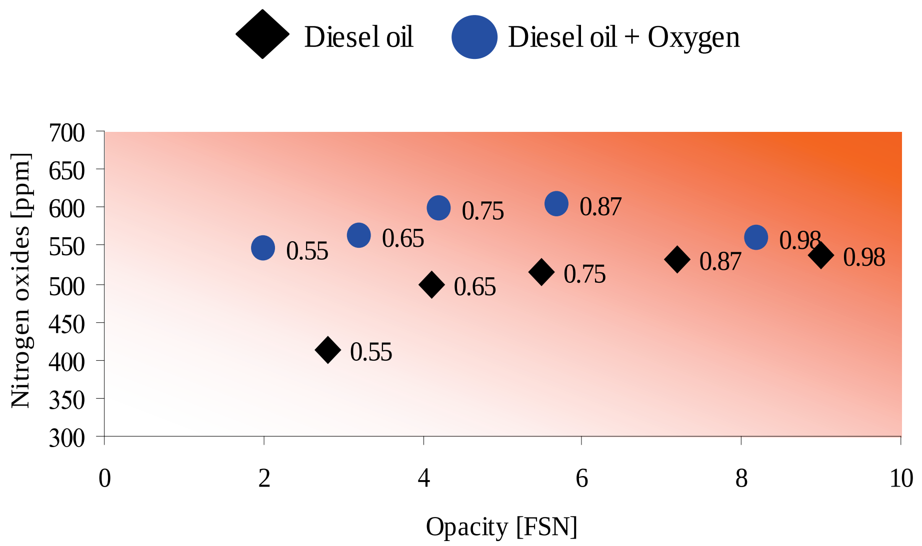

Fig. 7. Comparison of relative changes of the nitrogen oxides and opacity concentrations in exhaust gas

5. Conclusion

The observed changes in concentrations of the individual compounds in exhaust gas from the engine fuelled with diesel oil with dissolved oxygen can be undoubtedly referred to the changes occurring in the combustion process. The increase in the concentration of nitrogen oxides can prove that there is an increase in the temperature value in the flame front area and it also affects (results in) the increase in the combustion chamber temperature. This can be confirmed by the results of torque measurements the values of which increased by 5–20 % for the individual engine operating points. The obtained results show the positive changes of mutual correlation between the nitrogen oxides emission and the exhaust gas opacity especially in range of high engine load. The authors have gathered a rich experience resulting from their previous examinations carried out with the use of air and exhaust gas dissolved in diesel oil [3, 4]. Linking the present results with the previous ones they dare to say that fuelling the engine with diesel oil with dissolved air and exhaust gas gives better effects in reducing the concentrations of the toxic compounds in exhaust gas from the compression-ignition engines. Comparison of these examination results shows that the effect of releasing the gas dissolved in diesel oil, but not the oxygen concentration in the gas being dissolved, is a main factor affecting the improvement of the combustion process.

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