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Operation of diesel engine with fuels treated with nanoparticle additives

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Abstract. Treatment of materials with nano-sized elements is widely used in the automotive industry. This application is associated both with surface treatment of parts and in the form of various mixtures. The use of nanoparticles as an additive to oils and fuels aims to impact the energy efficiency of the engine in order to improve mechanical losses and its environmental performance. Improving mechanical losses leads to a reduction in energy consumption and hence to a reduction in carbon emissions. Published research in this regard has shown an impact on various physical processes related to engine performance. In this paper are shown the results from performed studies on a direct injected diesel engine when working with oil and fuel additives, based on carbon nanoparticles. The results show an improvement in the operation of the fuel injection system and reduction in the mechanical losses in the engine.

1. Introduction

The aim of the present study is to investigate the impact of carbon nanoparticles dispersed in biodiesel fuel mixtures on the operating parameters of a direct injection diesel engine.

A number of studies have shown increased thermal conductivity of nanofluids compared to untreated liquids. This medium is considered to be three-component, formed by a nanoparticle as the core and surrounded by an interfacial nanolayer as a shell, which in turn is immersed in the main liquid [1]. The size of the nanoparticles and the liquid boundary layer around the particles are a major factor for this increased thermal conductivity in solutions with nanostructure sizes in the range of 1-100 nm [2]. The coefficient of thermal conductivity depends on various factors such as concentration in the solution, shape and size of the nanoparticles, the degree of homogeneity of the solution and many others [3]. Studies have shown the impact of the thickness of the interfacial layers surrounding the nanoparticles on the total thermal conductivity of the nanofluid [4].

The thermal conductivity in nanofluids also largely depends on whether the nanoparticles remain dispersed in the main liquid, forming linear chain or similar configurations [5].

The fundamental understanding of the mechanism of increased thermal conductivity is not yet clear. The effect is used in various fields of technology where forced heat dissipation is required, in particular in electrical engineering and electronics. In internal combustion engines, nanofluids are extremely efficient for use as a cooling fluid [5].

In [6] a study was performed to determine the optimal concentration of nanoparticles of diesel fuel and Jojoba methyl ester. It has been found out that the use of Al_2O_3 additive in a concentration of about 20 mg/l improves the environmental performance of the engine, most notably for NOx emissions by 70%, CO by 80%, UHC by 60% and smoke by 35%. Studies of the working process of an internal combustion engine show that when increasing the concentration of Al_2O_3 to 40 mg/l there is a decrease in specific fuel consumption by 12% and an increase in the maximum value of pressure in the cylinder – p_{max}, the maximum growth rate of the pressure – $dp/d\varphi_{max}$, and the maximum heat release rate – $dQg/d\varphi_{max}$ by 4.5%, 4% and 4% respectively. According to the authors [6], the recommended concentration of Al_2O_3 in mixtures of diesel and Jojoba methyl ester is 30 mg/l, which leads to an improvement in both power-economic and environmental performance of the engine. For a period of operation lasting about two months, no erosive effects of Al_2O_3 on the fuel system and engine exhaust system were observed. The authors [6] are of the opinion that further research is needed in the long-term operation of the engine regarding the impact of this additive on the elements of the fuel system.

The addition of nanostructured particles to the fuel and lubricants significantly reduces friction. It has been found out that the coefficient of friction continues to decrease during continuous operation of systems with nanoadditives, which can be explained by roughness equalization [7]. It has been shown that nanosized particles are deposited on the surface of the material to form a layer. The nanostructured particles are in direct contact with the metal surfaces of the elements of the fuel system and it can be assumed that they settle on the contact surface. Experiments performed with a standard dispersion of 0.5 wt % TiO_2 particles, which was tested under standard conditions (pressure: 10 MPa; velocity: 0.16 ms^{-1}), showed an increase in the titanium detected in the surface layer. It is assumed that nanoparticles tend to adhere to the contact surface between the liquid and the metal [7].

Studies in [8] show a reduction in the roughness of contact surfaces when adding nanoparticles to lubricants. The phenomenon is described as polishing and has a significant effect on reducing friction. Comparative studies of steel disks on a rotating tribometer treated with AlMgSi structures show a reduction in friction when adding nanoparticles to the fluid compared to those when no additives were added [9]. It has also been shown that the effect of reducing friction is weakly dependent on the relative speed of movement, the base oil used, the dispersion additives and the nanofluid pre-treatment method used.

The duration of the ignition delay in the diesel combustion process largely determines the behaviour of the engine [10]. It consists of two main phases – physical and chemical, the identification of which is determined by the nature of the currently prevailing physicochemical processes. The duration of the individual phases depends mainly on the properties of the fuel and the thermodynamic characteristics of the medium in which the fuel is injected [11]. For biodiesel fuels, the duration of Ignition delay increases slightly due to the higher viscosity of these mixtures and reduced volatility during the fuelling process. Some of the characteristics of nanoparticles have the potential to affect mainly the physical phase of Ignition delay. The main ones are their increased thermal conductivity reaching in Carbon nanotubes (CNT) 2000 W/mK, Diamond – 600 W/mK, Al_2O_3 – 36 W/mK, while for diesel fuel it is about 0.15 W/mK. The addition of nanoparticles reduces ignition delay by shortening mainly its physical phase. The reason for this is the higher surface-to-volume ratio and the higher thermal conductivity of Al_2O_3 nanoparticles, which increases the evaporation rate.

2. Experimental set-up

An experimental study of the operation of a high-speed diesel engine working with B7 fuel was performed on an eddy current test stand [12, 13]. The test engine is a 4 cylinder, water cooled, direct injected diesel engine with rated power 46 kW at 4500 min^{-1}, torque 122 Nm at 2500 min^{-1}, displacement 1.993 cm^3, compression ratio 18:1.

Additives of nanomodified carbon structures (diamond) with sizes from 2 to 100 nm dispersed evenly in the fuel using an ultrasonic homogenizer were used. The experimental data required for the analysis were recorded with a high-sampling rate device capable of recording experimental data at 0.1 deg per engine crankshaft rotation angle. A developed methodology was used for preliminary and subsequent processing of the experimental data registered with automated systems, in order to study the registered processes through derivatives of higher order. The workflow data are obtained by processing sequential single diagrams, each for itself, after which the characteristic result points are averaged for the specific mode of operation of the engine. The engine operates on load characteristics at maximum torque mode. To ensure sufficient time for the nanostructured particles to be in direct contact with the metal surfaces of the elements of the combustion system, for deposition on the surface of the material and for the formation of a nanolayer, the engine runs continuously with nanomodified fuel. The results of the measurements were obtained after running the engine for 13 hours.

3. Results and discussions

The duration and limits of the Ignition delay as well as the phases of the period, physical and chemical, are determined along the lines of the heat release rate.

3.1. Ignition delay

3.1.1. Physical phase. The graphs show a significant reduction in the physical phase of Ignition delay. For the shown operating modes of the engine, the average values of the duration of the physical phase when working with nanoadditives to the fuel are about 3.3 deg crankshaft rotation angle (CA) smaller than those when working without additives. Figure 1 shows a decrease in the duration of the physical phase of Ignition delay by about 28.7%. The physical processes of fuel dispersion immediately after the start of fuel injection and the evaporation of fuel droplets are probably strongly impacted by the increased thermal conductivity and accelerated heat transfer in the direction from environment with a higher temperature to the currently injected fuel. At the same thermodynamic parameters of the medium at the beginning of the fuel supply in the diesel engine there is an acceleration of the processes of fuel dispersion and evaporation.

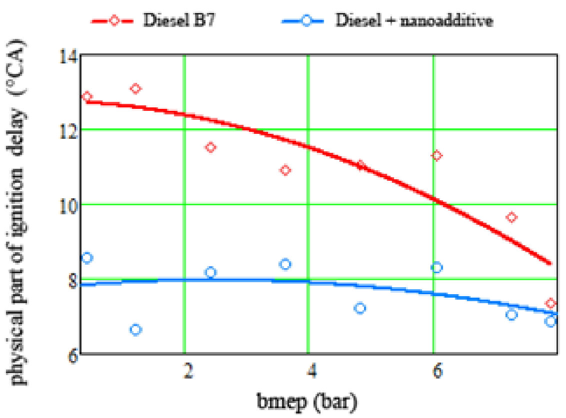

Figure 1. Duration of physical part of ignition delay vs brake mean effective pressure *bmep*.

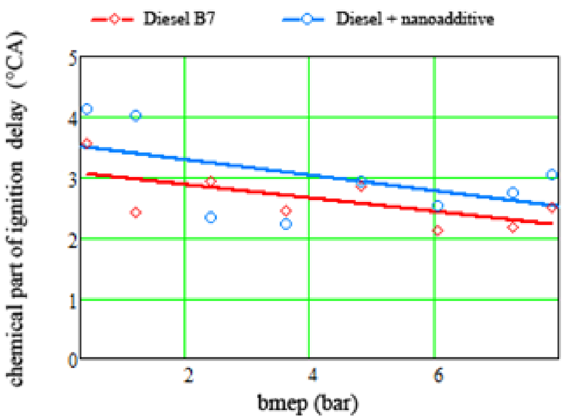

Figure 2. Duration of chemical part of ignition delay vs brake mean effective pressure *bmep.*

3.1.2. Chemical phase. The duration of the chemical phase of ignition delay is shown in figure 2. There is a certain delay in the process here. The duration of the chemical phase increases on average by about 0.4 deg, which at an average value of the order of 2.6 to 3.0 deg, is 15.4%.

3.1.3. Total ignition delay. Figure 3 shows the total duration of the ignition delay. The average decrease is of the order of 2.9 deg and represents a decrease of 13.6%. The ratio of the two phases changes. For the tested engine, the duration of the physical phase for engine operating modes by load characteristic occupies about 80.5% of the total duration of Ignition delay. After treatment of the fuel and operation of the engine with the addition of the studied nanostructures, the share of the physical phase decreased to 71.9%.

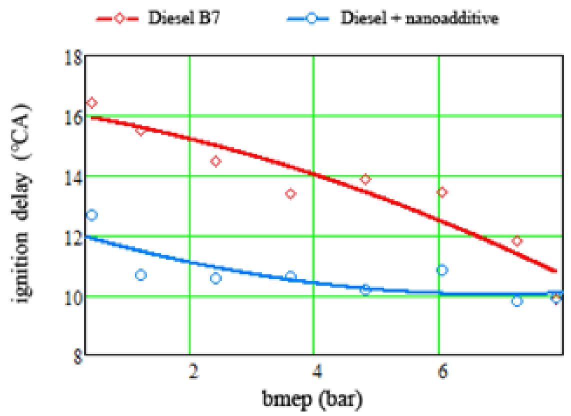

Figure 3. Ignition delay, determined by line of heat release rate, vs brake mean effective pressure *bmep.*

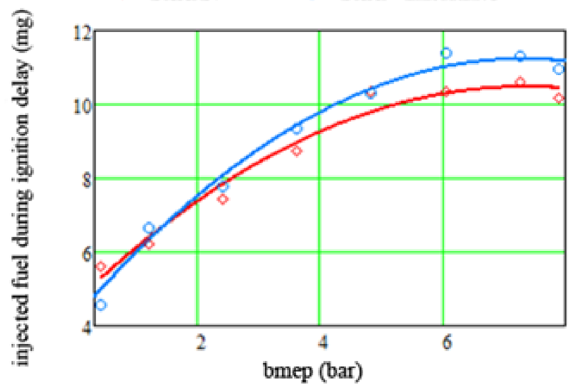

Figure 4. Quantity of injected fuel during ignition delay in mg vs brake mean effective pressure *bmep.*

3.2. Injected fuel during ignition delay

Prolonged operation of the fuel system with fuels with added carbon nanoparticles reduces the roughness of internal surfaces and this implies a reduction in hydraulic resistance. This phenomenon probably leads to a change in the differential characteristics of fuel supply, changing the amount of fuel injected during the different phases of the combustion process in diesel engines. Figure 4 shows the amount of fuel entering the engine's combustion chamber during Ignition delay. The amount of fuel injected during Ignition delay increased for all tested modes by an average of 0.347 mg, which is an increase of about 2.9% on average. The same graphs show that this increase is not the same for all engine modes. In the area of low loads such an increase is absent, even a reverse downward trend is seen.

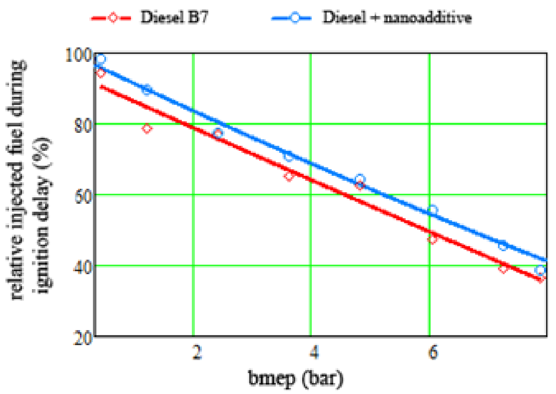

Figure 5. Relative quantity of injected fuel during ignition delay vs brake mean effective pressure *bmep.*

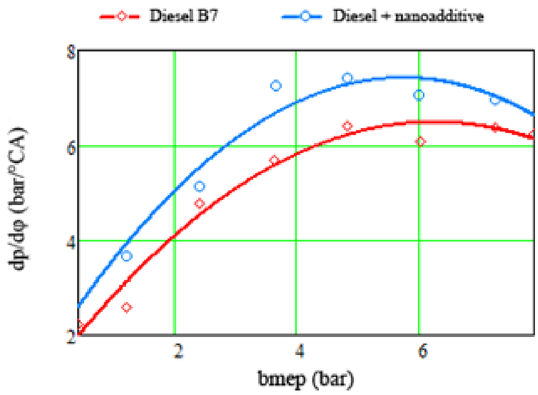

Figure 6. First derivative of in-cylinder pressure *dp/dφ* vs brake mean effective pressure *bmep.*

Figure 5 presents the results for the amount of fuel injected through the ignition delay relative to the cycle portion of fuel for the respective engine mode. Both dependences are equidistant, have the character of straight lines, although they are obtained by regression smoothing of the experimental data with a polynomial of the second degree. The average difference between them for the different operating modes of the engine is almost the same, its value is 5% and represents the increased relative amount of fuel, injected through ignition delay.

3.3. Rate of pressure rise

Reducing the duration of the Ignition delay leads to improved engine performance in indicators such as a lower maximum rate of increase in cylinder pressure. This results in reduced maximum values of pressure in the cylinder, low level of vibrations and noise, improved environmental performance and more.

The obtained values for the maximum rate of pressure increase in the engine cylinder, figure 6 shows an increase compared to the baseline. For all studied regimes, the average value of this parameter from 5.05 bar/deg CA was increased to 5.8 bar/deg CA, which is an increase of 16.5%. Despite the registered decrease in the duration of Ignition delay, by significantly shortening its physical phase, the increase in the relative share of fuel injected during this period obviously predetermines the further development of the combustion process during the premixed combustion phase.

4. Conclusion

The addition of diamond carbon nanoparticles to biodiesel fuel mixtures leads to a change in the studied parameters of the combustion process of the tested diesel engine. The increased thermal conductivity of these mixtures has a positive effect on the processes of fragmentation and evaporation, which take place at the beginning of the fuel supply to the engine cylinder. These processes have a strong impact on the duration of the physical phase of ignition delay and practically do not affect its chemical phase.

Prolonged operation of the fuel system of the engine with nanoadditives in fuel changes the differential characteristic of fuel injection. This leads to an increase in the relative amount of fuel injected into the engine cylinder during ignition delay, relative to the whole injected fuel per cycle. This change in the fuel supply characteristic has a decisive impact on the maximum values of the rate of increase of pressure in the engine cylinder.

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