

The assessment of ecological parameters of diesel engine supplied with mixtures of canola oil with n-hexane

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Abstract. As a result of the increase of ecological awareness and restrictions for fumes emission, numerous studies have been conducted which aim at improving power supply systems and the structure of diesel engine. Another course of action taken to adjust to rigorous fumes emission norms is the replacement of hydrocarbon fuels with alternative ones. The research on the engine dynamometer, conducted by the authors, showed that the application of the mixture of canola oil with n-hexane positively influenced certain ecological parameters of the engine, particularly the nitric oxide (NO_x) emission. Due to law regulations concerning the level of emission of toxic substances of exhaust gases, which require monitoring in real road traffic conditions, the attempts have been made to assess ecological parameters of diesel engine supplied with mixtures of canola oil with n-hexane. This article presents the research results for diesel engine in real operating conditions. The exhaust gas tester – Herman HGA 400 – was used for measuring ecological parameters. The level of the main toxic substances was measured during the research (CO, HC, NO_x) and CO₂, O₂. The ecological parameters for diesel engine supplied with the mixture of canola oil and n-hexane were compared to those for diesel engine supplied with diesel fuel.

1. Introduction

Rapid growth of the number of vehicles and restrictions concerning the emission of toxic substances of exhaust gases result in scientific work aimed at searching for new types of fuels for powering internal combustion engines [[1],[5],[6],[7],[20]]. With respect to diesel engine the main focus was on acquiring fuels not from petroleum refining, the so-called alternative fuels (bio-fuels)[[8],[17],[18]]. It is claimed that obtaining energy from bio fuels is one of the key elements of economic development, which is beneficial ecologically, energetically and economically. Nowadays, limiting carbon dioxide emission to the atmosphere is a crucial issue. Therefore, using bio fuels made from oilseeds has considerable advantages. It can be assumed that the amount of CO₂ for bio fuels is similar to that of plants in the process of photosynthesis in the period of plant growth (closed circuit CO₂)[[6],[10],[11],[17],[18],[19]]. It largely influences the increase of global warming. The regulations concerning the limits of the emission of toxic substances of exhaust gases, such as nitric oxides (NO_x), particles (PM), hydrocarbons (HC), carbon oxides (CO) and carbon dioxide (CO₂) apply to most mechanical vehicles sold in the EU. Moreover, they are sanctioned by the EU with EURO norms [[3],[4],[23],[24]]. The restrictions apply to heavy goods vehicles, passenger cars, buses, trains, tractors and agricultural machines. According to the regulations, (since 1/09/2016) diesel engines have to comply the EURO 6 norm which lowered the accepted level of nitric oxide by 60%. The authors of the article ran a series of tests on the engine



dynamometer in static and dynamic conditions. During the tests, the diesel engine was powered (among others) with canola oil with various additives [8,9,[14],[15],16]. One of the research stages was the application of canola oil with n – hexane (in various proportions V/V) [[12],[13],[25],[28]]. Although the results were promising, they did not reflect the work of an engine in real road conditions. The tests run on the engine dynamometer showed that using the mixture of canola oil with n-hexane had a positive influence on certain ecological parameters of the engine, particularly on the emission of nitric oxides (NO_x). The test (static and dynamic) were conducted on the engine dynamometer, where the object of study was an AD3.152 engine without the forced induction or exhaust gas recirculation (EGR). Due to law regulations concerning the level of toxic substances of exhaust gases which require emission control in dynamic conditions, the ecological parameters of diesel engine, powered with the mixtures of canola oil and n-hexane, were investigated in such conditions. The article presents the results of tests on the diesel engine in real operating conditions (in real road traffic). The tested engine was equipped with a turbocharger with a dump valve (without variable turbine geometry), the Common Rail direct fuel injection, the exhaust gas recirculation system (EGR) and the diesel particulate filter (DPF). The exhaust gas tester – Herman HGA 400 – was used for measuring ecological parameters, its probe was placed in the exhaust system, behind the diesel particulate filter (DPF). The levels of the main toxic fumes substances were measured (CO , HC , NO_x) and CO_2 i O_2 . The results were compared with the ones for diesel oil. The tests focused on gas emission behind the catalytic converter.

2. The specificity of the course of the combustion process in the diesel engine fuelled with the mixture of canola oil with n-hexane

Canola oil applied as fuel for diesel engine causes certain difficulties resulting from its physicochemical properties which differ from those of diesel fuel (Table 1). One of the main physicochemical parameters of the fuel influencing the injection process, and thus indirectly the process of combustion, is the viscosity. Disorders in the process of combustion cause the increase in the emission of toxic substances of exhaust gases – mainly nitric oxides NO_x - and the level of particulate matter (PM). Consequently, pure canola oil is not commonly applied to power car engines. The relative difference in density between diesel fuel and canola oil is about 7% and should not influence significantly the process of creating combustible mixture, though the fuel density is crucial for a number of parameters for a stream of sprayed fuel. In the combustion process in the diesel engine there are two phases: kinetic combustion and diffusion combustion. They occur interchangeably and influence the combustion process and thus the production of toxic substances. Kinetic combustion is connected with obtaining a homogenous mixture. Homogeneity of the combustible mixture results (among others) from high injection pressure which contributes to shrinking of the drops of fuel and therefore, to their easier evaporation. Diffusion combustion occurs in heterogenic mixture – an evaporating drop, which is the source of the fuel steam, combusts in the air as a diffusion flame around the drop [[1],[2],[27]]. Toxic substances emission is inseparably connected with the fuel combustion process. One of the basic products of complete combustion is carbon dioxide (CO_2). Oxygen deficiency results in incomplete combustion and then carbon oxide (CO) appears in the exhaust fumes. Nitric oxides NO_x (NO i NO_2) occur during combustion and their appearance is connected with the temperature of combustion and the presence of oxygen and nitric compounds in the fuel. Fig. 1 shows the chart of the combustion mixture structure (described by the stoichiometric coefficient ϕ , adiabatic temperature of the flame – T), where the area of the particles production (PM), the area of nitric oxides production (NO_x) and the area of the combustion process in a typical diesel engine are visible [[2],[27]].

In order to limit the amount of highly toxic nitric oxides (NO_x) additional systems were introduced for diesel engines. They allow to divert part of the exhaust fumes back to the combustion chamber in order to (among others) lower the temperature. The specific heat of neutral products of combustion (CO_2 , H_2O) is higher than that of air, thus those products influence the lowering of the circuit temperature [[10]]. The amount of recycled exhaust fumes is controlled with a valve (known as EGR valve). However, diverting the exhaust back to the combustion chamber is connected with the

increase of the particulate matter (PM), which can be limited by increasing the ratio of the combustion mixture.

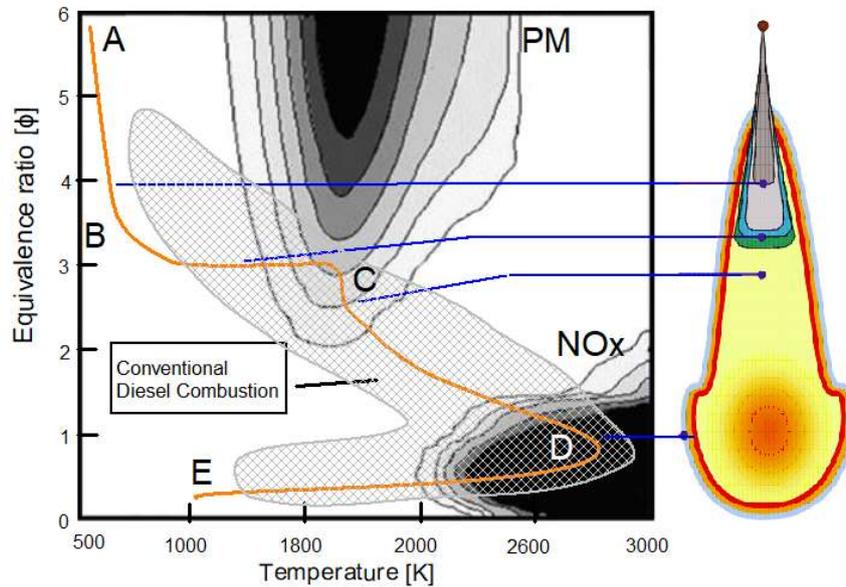


Figure. 1 The combustion process in diesel engine – part A-B ignition delay, part B-C the phase of kinetic combustion, part C-D diffusion combustion phase, part D – E the phase of post-combustion in the area $\phi < 1$. On the left of the ϕ -T chart there is a model of a combusting stream of fuel in a quasi-steady state [[2],[27]]. Fuel ratio ϕ , which is the inverse of the air – fuel $\lambda(\phi=1/\lambda)$.

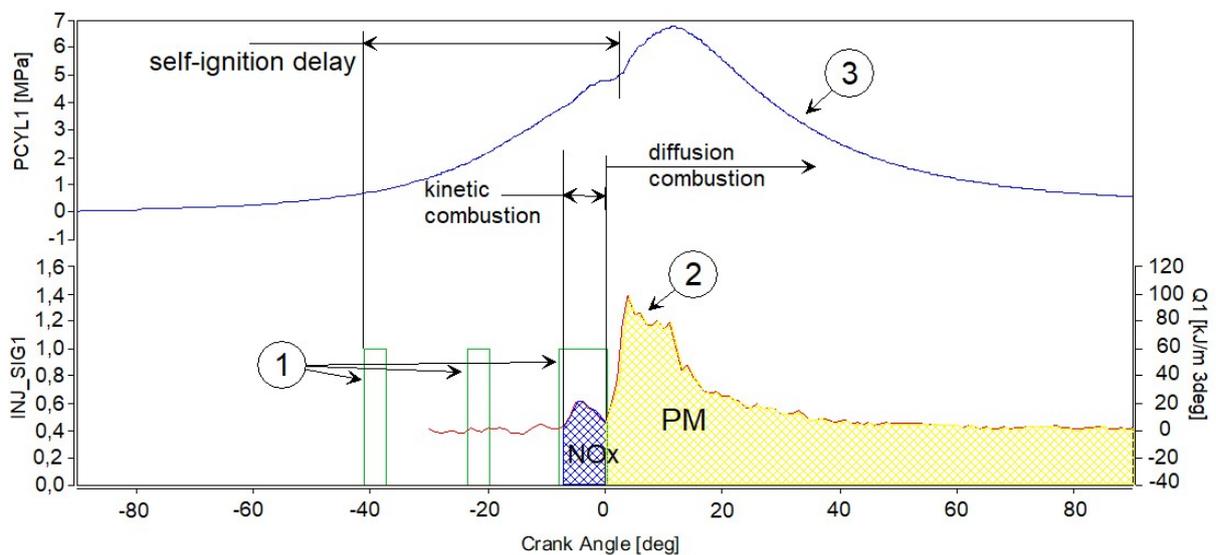


Figure. 2 The process of combustion of a stream of diesel fuel in diesel engine with direct injection system. The phases of the process, which are responsible for the control of the emission of NO_x and PM, are marked in the function of rotation angle of the crankshaft [[27]]. (1) marks the fuel injection, (2) the speed of heat production, (3) the pressure in the combustion chamber.

Figure 2 presents the process of combustion of a stream of diesel fuel in diesel engine with direct injection system. The phases of the process, which are responsible for the control of the emission of NO_x and PM, are marked in the function of rotation angle of the crankshaft [[27]].

The chart (Figure 2) show that in the period of spontaneous ignition delay there already occurs uncontrollable (kinetic) combustion, during which the steam around the stream of fuel is burnt. The process of kinetic combustion of diesel fuel sprayed into the combustion chamber in the phase of the ignition delay is connected with the lack of time needed to mix the fuel with air. As a result, local spheres with high air – fuel ratio are created which contain, which contributes to low level of the emission of particles, carbon oxide and unburned hydrocarbons. The pressure in the combustion chamber grows rapidly and reaches the phase of controlled (diffusion) combustion. At that moment, the pressure in the combustion chamber is at its highest value. The air – fuel mixture ignition causes a dynamic combustion process with high speed, the increase of the pressure and temperature in the combustion chamber, generating nitric oxides and the noise emission. The speed of heat production during diffusion combustion depends mostly on the intensity of the process of creating the air-fuel mixture (which is directly influenced by the physicochemical properties of fuel, diffusion processes and turbulence). In the final phase of combustion there is a period of post – combustion, during which unburned remains of fuel are chemically transformed because of the hot exhaust fumes. Post-combustion is a process which disadvantageously lowers the heat efficiency of the engine and the fuel consumption [[2],[27]]. Although canola oil technically has certain qualities better than diesel fuel (e.g. large amount of oxygen compounds in the fuel), due to specific physicochemical properties, it greatly influences the process of the production of the air – fuel mixture. [[17],[18]]. Diesel engine burns fuel in the excess of oxygen (weak mixture). In the process of complete combustion there should not be unburned hydrocarbons or oxygen in the exhaust fumes. Canola oil has much weaker volatility and the tendency to spontaneous ignition, and is characterised by high temperature of thermal decomposition. Those factors can have a huge influence on the increase of NO_x and PM emission. One of the tested ways of limiting the drawbacks of supplying diesel engines with canola oil is adding n-hexane to the mixture. Due to significant improvement of physicochemical parameters (especially viscosity) it seems possible to enhance such parameters as: injection parameters, evaporating of the fuel (the drops of sprayed fuel have smaller diameters) and the combustion process. As a result of data analysis, running preliminary tests and all the above mentioned dependencies, the optimal volume composition of the chemical additive to canola oil, which was n-hexane, was estimated. Surface tension, density and viscosity of n-hexane are much lower than those of diesel fuel and pure canola oil [[12],[28]]. Consequently, the following fuels were subjected to further analysis:

- diesel oil - Df
- canola oil - Co
- canola oil with 10% n-hexane - 10%Hex90%Co.

Main physicochemical properties of canola oil with n-hexane were tested and the results are presented in Tab.1 [[28]]. After the results analysis, it can e stated that mixtures of n-hexane and canola oil start to distil in the temperature of about 60°C and cease to distil in around 100-110°C. In the temperature above 250 °C decomposition of canola oil is visible (the amount of the distillate was adjusted to the amount of hexane added to the mixture). N-hexane additive greatly influenced the combustion temperature of the mixture mainly due to its volatility and low ignition temperature (-22°C)[[21]]; and it slightly influenced the decrease of the created mixtures density. The Physicochemical qualities and the research methods for the diesel fuel used for testing were in accordance with the Polish norm: PN EN 590:2013 [22].

In preliminary tests on the engine dynamometer a series of works was done [[12],[13],[15],[25]], during which the parameters of the engine work in dynamic conditions and static conditions (imitated with the use of the external exploitative characteristic) were compared. The object of the study was a compression ignition engine AD3.152 with direct injection characterised with one constant fuel injection per cycle. On the basis of the tests it was stated that:

- emission of nitric oxides (NO_x) was lower for the mixture of canola oil with n-hexane and for pure canola oil in comparison with diesel fuel.
- the amount of other toxic substances in exhaust fumes (CO, CO₂, HC and particulate matter - PM) for canola oil with n-hexane was significantly different from the parameters for diesel fuel.

Table 1. The main results for the physicochemical properties of the tested fuels[28]

Type of fuel	Density in 20°C [kg/m ³]	Kinematic viscosity indicator 40°C [mm ² /s]	Surface tension [mN/m]	Ignition temperature [°C]
Co	920.7	34.89	34.15	199
10%Hex90%Co	900.1	19.64	30.08	<40
Df	840	2.7	29.15	72

Due to the development of compression ignition engines, traditional injection systems (e.g. rotation pump or injection pump) are replaced with direct fuel injection systems in which the injection strategy (several fuel injections per one work cycle) is immediately corrected by a controller. The exhaust monitoring system with the use of probes also has a significant influence on the parameters of injected fuel (dosage correction). In this article, the authors attempted to present ecological parameters of the engine operating in static conditions in real road traffic. The conditions of the engine's work reflected typical conditions of the vehicle functioning. The engine was equipped with Common Rail direct fuel injection

3. Empirical research

3.1. The research stand, the researched object

The research was conducted in the Laboratory of the Department of Car Vehicles at the University of Technology in Lublin. The object of tests was Fiat Qubo with a self-ignition engine fulfilling all emission standards specified by Euro 5 and a five speed gearbox. In the tested vehicle an additional fuel supply system, with an exchangeable fuel tank was installed. The main technical parameters of the tested car engine are shown in Table 2.

Table 2. The main technical parameters of 1.3 Multijet engine of the tested vehicle - Fiat Qubo.

Number of cylinders	4
Cylinder diameter (mm)	69.6
Piston stroke(mm)	82
Total engine cubic capacity (cm ³)	1248
Maximum power (kW CEE)	55
Maximum power (KM CEE)	75
Functioning at maximum power (rpm)	4000
Maximum torque (Nm)	190
Maximum torque (Nm) (kgm CEE)	19.4
Rotational Speed at maximum torque (rpm)	1500
Revolutions at neutral gear (rpm)	850 ± 20
Compression ratio	16.8 : 1

The system for indicating the engine Indi Micro 602 made by AVL with a built-in signal amplifier, cooperating with four analogue input channels and two digital inputs was used in tests. The signals recorded by the AVL Indi Micro system are the following:

- the course of pressure inside the cylinder – it was recorded by means of a piezoelectric sensor AVL GH13P installed in the glow plug seating of the first cylinder;
- the signal of engine crankshaft position;
- injection parameters were analysed on the basis of the analogue signal of controlling the electromagnetic injector after converting it into the digital signal.

For measuring the level of toxicity the exhaust gas tester – Herman HGA 400 – was used (made by Pierburg Instruments). The device allows for the measurement of the levels of CO, CO₂, HC, O₂ i NO_x.

The exhaust fumes were collected directly from the end of the exhaust system. The mobile exhaust gas tester – Herman HGA 400 is presented with a technical description in figure 3. Figure 4 demonstrates the mobile research stand used for testing.



Figure 3. The mobile exhaust gas tester – Herman HGA 400 and its technical specification.



Figure 4. The mobile research stand: 1 Fiat Qubo with a 1.3 Multijet 2 engine. 2. The place of the AVL sensor installing – glow plug socket for the first cylinder. 3. Measurement pincers – obtaining the control signal with the first cylinder injector 4. The spot of receiving the signal of the GMP sensor – inductive sensor. 5. The elements of the additional fuel system – A. Valves, B. The transmitter with the fuse controlling the additional fuel pump. C. Additional exchangeable fuel tank. D. The switch of the additional fuel system. 6. The measuring AVL module and the AVL Universal Pulse Conditioner

converter. 7. Flow fuel consumption meter with the PMZP recorder. 8. Computer with the AVL software. 9. Mobile exhaust gas tester Herman HGA 400

3.2. The research methodology

The compression ignition engine installed in the vehicle was subjected to induction in selected movement conditions reflecting static conditions during which the level of toxic substances in the exhaust fumes was registered. The tests were run in the vehicle moving in real road traffic. The vehicle was subjected to motion resistance forces.

During the tests, the following two cases were analysed:

- Case 1 - stop – engine neutral gear, conditions of static engine work with rotational speed from 800 to 4000 rotations per minute.
- Case 2 - driving in the fourth gear on even, smooth surface of a straight, asphalt expressway (direct gear)– conditions of static engine work, constant load from rolling resistance forces;

4. Analysis of the obtained results

Pictures 5 to 7 present the results of the measurement of ecological parameters for the engine operating in selected conditions. The emission of nitric acid (NO_x), carbon oxide (CO), carbon dioxide (CO_2), hydrocarbons (HC) and oxygen (O_2) was analysed. The tests were run for the static conditions of the engine work (case 1 and 2). The analysis of the exhaust gases emission for the engine powered with plant fuels, without load, in static conditions (case 1) showed that in the full range of rotational speed the emission of nitric oxide (NO_x) was higher than for diesel fuel. The most significant relative difference occurred for the engine supplied with canola oil with n-hexane in comparison with the one supplied with diesel fuel; the difference was about 300% for the rotational speed of 800 rpm (neutral gear). With the increase of rotational speed the difference became smaller and for the speed of 4000 rpm it was only 33% (Figure 5, picture A). For case two (driving at constant speed) the differences in the nitric oxides (NO_x) were not as significant as in case 1. The smallest relative difference occurred for the engine supplied with canola oil with n-hexane in comparison with the one supplied with diesel fuel occurred for rotational speed 2500 rpm and it was 2%. With the increase of rotational speed the difference became bigger and for the speed 4000 rpm it was 67% (Fig. 5, pos. B). Adding n-hexane caused that nitric oxide (NO_x) emission was higher also in comparison to pure canola oil (Figure 5, picture A).

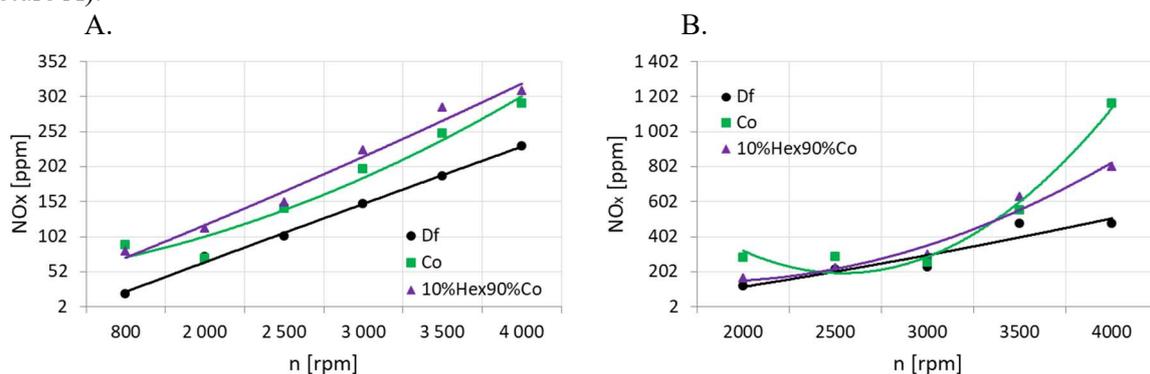


Figure 5. The course of the concentration of nitric oxides (NO_x) in exhaust fumes depending on rotational speed, for diesel engine powered with the tested fuels. A. Case 1 – neutral gear, B. Case 2 – driving in fourth gear in real road traffic conditions. Black colour – diesel oil, green colour – canola oil, purple colour – canola oil with n-hexane 10%Hex90%Co.

The analysis of carbon dioxide emission (CO_2) for the engine powered with plant fuels in static conditions without load (case 1) showed that for the full range of rotational speed the emission was higher than in case of diesel fuel. The most significant relative difference occurred for canola oil for the speed of 800 rpm (neutral gear) and it was 37%. For canola oil with n-hexane the difference was 30%

for the rotational speed of 3500 rpm (Fig. 6, pos. A). Similarly, in case 2 (driving at constant speed) carbon dioxide (CO_2) emission, in the full range of rotational speed, was higher for the engine supplied with canola oil than for diesel oil. The most significant difference was 43% for the speed of 4000 rpm. In case of the engine supplied with the mixture of canola oil and n-hexane, in the range of rotational speed up to 3000 rpm, carbon dioxide emission (CO_2) was lower when compared to diesel fuel; with the biggest difference for the speed of 2000 rpm – about 11%. With the increase of rotational speed, carbon dioxide emission escalated. For the speed of more than 3000 rpm its emission was higher than in case of diesel fuel, reaching the biggest relative difference (12%) for the speed of 3500 rpm (Figure 6, picture B)

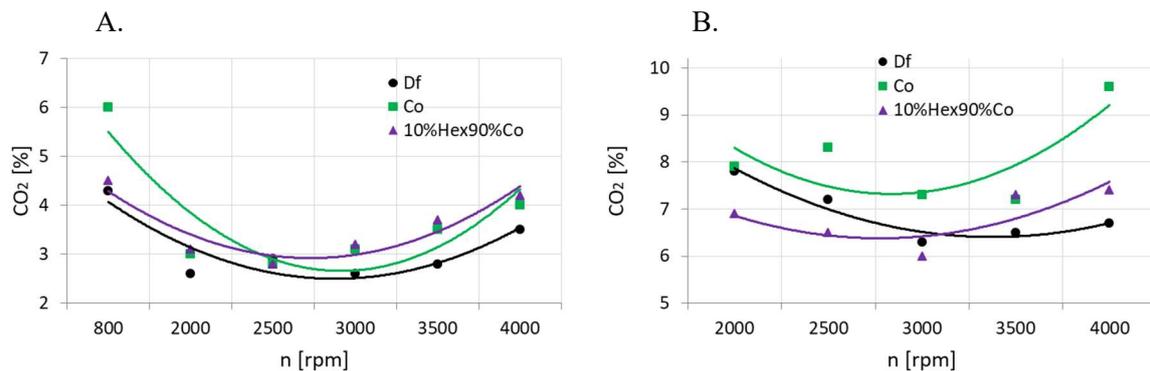


Figure 6. The course of the concentration of carbon dioxide (CO_2) in exhaust fumes depending on rotational speed, for diesel engine powered with the tested fuels. A. Case 1 – neutral gear, B. Case 2 – driving in fourth gear in real road traffic conditions. Black colour – diesel oil, green colour – canola oil, purple colour – canola oil with n-hexane 10%Hex90%Co.

Static engine work without load (case 1) almost in the full range of rotational speed generated slightly bigger amount of oxygen (O_2) for the engine supplied with diesel fuel when compared to plant fuels. For canola oil with n-hexane the biggest relative difference occurred for the rotational speed of 3500 rpm and it was only 6%. For the speed of about 2500 rpm the amount of oxygen (O_2) was slightly bigger (for both cases of plant fuels) than for diesel fuel; the difference was about 2% (Figure 7, picture A). While analysing case 2 a reversed tendency is visible in comparison to case 1. In the range of rotational speed of about 3000 rpm, plant fuels were characterised by bigger amount of oxygen (O_2) in exhaust fumes when compared to diesel fuel. In the tested conditions the biggest amount of oxygen (O_2) was generated by the mixture of canola oil with n-hexane. The most significant relative difference occurred for the speed of 2500 rpm and it was 37%. From the speed of 3000 rpm the amount of oxygen (O_2) in the exhaust fumes was bigger for diesel fuel than for plant fuels, reaching its highest value for the speed of 4000 rpm, where the relative difference was 20% - when compared to canola oil (Figure 7, picture B)

The tests were conducted for the emission of gases behind the catalytic converter and the diesel particulate filter. Trace amount of carbon oxide (CO) and hydrocarbons (HC) was registered in the exhaust fumes.

A.

B.

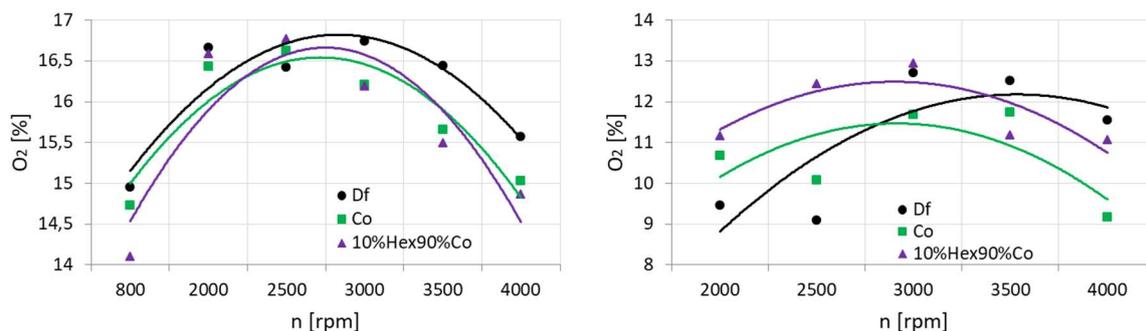


Figure 7. The course of the concentration of oxygen (O_2) in exhaust fumes depending on rotational speed, for diesel engine powered with the tested driving in fourth gear in real road traffic conditions.

Black colour – diesel oil, green colour – canola oil, purple colour – canola oil with n-hexane 10%Hex90%Co.

5. Conclusions

Physicochemical properties of canola oil, which are different than those diesel fuel cause certain difficulties while applying them for powering diesel engine. It particularly concerns the oil viscosity, especially in low temperatures. Consequently, supplying engines with such fuel without crucial structural modifications is not possible. Adding n-hexane as a non – reactive solvent to canola oil results in a positive change of physicochemical properties of the mixture, particularly with respect to its density and viscosity. The analysis of the course of ecological parameters demonstrates that:

- adding 10% n-hexane to canola oil improved the physicochemical properties of the fuel towards diesel fuel.
- the tests were conducted for the emission of gases behind the catalytic converter and the diesel particulate filter. Trace amount of carbon oxide (CO) and hydrocarbons (HC) was registered in the exhaust fumes of all the tested fuels..
- for pure canola oil (Co) and the mixture of canola oil with n-hexane (10%Hex90%Co) the level of NO_x emission was higher when compared to diesel fuel; preliminary tests showed the reversed tendency for non-loaded engine with direct injection without the exhaust recirculation system; the observed difference resulted from the fact that the engine of the tested vehicle was equipped with forced induction system and the EGR, which was connected with a more intensive combustion process.
- the work of the engine supplied with canola oil and the mixture of canola oil with n-hexane is possible in real road conditions of a vehicle movement; the only problem, when ecological standards are concerned, is the increase in nitric oxides emission – further research of the authors of this article will be devoted to the issue of limiting that problem.

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