TEKA Kom. Mot. Energ. Roln. – OL PAN, 2011, 11, 29–39

THE PROPERTIES OF A HDV DIESEL ENGINE FUELLED BY CRUDE RAPESEED OIL

Jerzy Cisek*), Andrzej Mruk*), Vladimir Hlavňa**)

*) Jerzy Cisek, Ph.D., M.E., Andrzej Mruk, Prof., Cracow University of Technology Poland
**) Vladimir Hlavňa, Prof. University of Žilina, Slovakia

Summary. The article presents the results of investigation of a 500 kW diesel engine fuelled by crude rapeseed oil. The authors discuss technical problems of adapting the engine to work on rapeseed oil and of using additives, which provide engine operation without breakdown. Measurements of energy parameters and of exhaust gas toxicity were done. The test methods and the measurement apparatus were in accordance with the ECE standards. As the engine was the integral part of the generating set, the measurements were conducted at constant rotational speed n=1500 rpm and at changing engine load. As a result of the performed investigation it was stated that the use of rapeseed oil instead of gas oil causes the increase of the fuel consumption per hour (without affecting the total efficiency), the increase of nitric oxides (NO_X) as well as the emission of particulate matter (PM). In consequence of the investigation it can be confirmed that high-power diesel engines can be fuelled by crude rapeseed oil, provided that both the engine and the fuel is adapted to this purpose.

Key words: crude rapeseed oil, energy parameters, exhaust gas, particulate matter

1. INTRODUCTION

The vast majority of research centres dealing with the problem of fuelling the combustion engines by vegetable fuels concentrate on the rape oil methyl esters instead on the crude vegetable oil. It is due to the fact that “crude” vegetable oils differ considerably in physical and chemical properties from the gas oil. However, manufacturing costs of the crude vegetable oil are significantly lower than the costs of the methyl esters, for example – of the rapeseed oil. Therefore, this study presents the results of examining a Perkins 2806A-E18TAG2 Diesel engine of power rating 500 kW. The engine was integral part of a generating set, fuelled by rapeseed oil without chemical modification to the RME form.

2. PHYSICAL AND CHEMICAL PROPERTIES OF RAPESEED OIL

Crude rapeseed oil is a mixture of different glycerides, i.e. compounds of fatty acids. Unfortunately, due to the different botanic forms of the rape, climatic conditions and stamping technology (cool or hot forming), physical and chemical properties of the rape oil may significantly differ [11-

16]. The Table 1 contains the mean values of the parameters characteristic for the rape oil compared with the properties of the gas oil.

Table 1. Comparison of the physical and chemical properties of the rapeseed oil and the gas oil [1-7]

Parameter \ Fuel	Unit	Gas oil	Vegetable oil
Molecular mass	-	ca 280	max. 850
Density at 20°C	g/cm^3	0.825	max. 0.915
Kinematic viscosity at 20°C	mm^2/s	ca 4	max. 70
Surface tension at 20°C	N/m	ok. 24 10^{-3}	max. 35 10^{-3}
Calorific value	MJ/kg MJ/dm^3	42.6 35.2	min. 38.0 min. 34.5
Average elementary composition • C • H • O	% mas.	87.0 13.0 0.0	77.0 12.0 11.0
Sulphur content	% mas.	max 0.2	max. 0.001
Water content	mg/kg	-	300-max 700
Free fatty acids content.	% mas.	-	0.8-1.3
Cetane index LC	-	45-55	ok. 40
Ignition temperature	K	440	470-550
Cloud point	K	265	260 -270
Cold filter blocking temperature	K	260	285-300
Freezing temperature	K	260	250
Destillation run • Start • 50% • 85%	K	• 450 • 565 • 600	• 315–max.430 • ca 600 • ca 620
Heat of vaporization	kJ/kg	230	max. 830
Stoichiometric constant	kg/kg	14.5	12.5

3. ADAPTATION OF THE ENGINE TO WORK ON RAPE OIL

Due to the important differences in rape oil properties in comparison to the gas oil, adapting the engine to work on crude rapeseed oil involved not only changing the supply and control engine systems, but also applying appropriate packs of additives to the vegetable oil.

The most important changes in the engine supply system are presented below:

1. Use of separate fuel tanks for vegetable oil and gas oil. The tank containing rapeseed oil had an automatic temperature control system (60^{o}C),
2. Use of a special heated fuel filter, engaged automatically with the engine supply system, when the engine operated on vegetable oil,

Change of the control engine software consisting, among other things, in controlling the rape oil temperature, automatic switching over of the engine supply system on the rape oil after starting the engine and getting the required temperature of the vegetable fuel, as well as automatic switching over of the fuel system on the gas oil after the command "stop engine". The engine was stopped automatically only after the supply system was flushed with the gas oil.

The discussed above construction and control changes in the engine adapted to the operation on the rape oil, result from two essential facts. In the ambient temperature, the kinematic viscosity of the rape oil is more than 18 times higher in relation to the gas oil. It results in deterioration of the processes of injection, atomization, evaporation, self-ignition and combustion of the rape oil as compared with the gas oil. Heating the rape oil up to the temperature 60^{o}C equalizes these inconveniences influencing as well the engine energy parameters as the exhaust gas toxicity [8]. Moreover, vegetable oils (except for olive oil) are prone to self-oxidation [9]. Practically, it means that they dry up forming a very durable layer, which, under engine operation conditions, leads to the immobilization of the injection apparatus precise pairs during the engine standstill. For this reason, stopping of the engine followed automatically the switching over the supply system to work on gas oil.

Phot. 1. Overall view of the generating set with the examined engine Perkins 2806A-E18TAG2

Phot. 2. Engine Perkins 2806A-E18TAG2
with a special, heated rape oil filter. View of a part of supply system.

Considering the differences in physical and chemical parameters of the gas oil as compared with the rapeseed oil (crude, not degummed), in the case of the vegetable oil, two additives were used:

– the additive washing the engine injection system, produced by the firm *Kleen-flo*, 300 ml for 200 l of the rape oil,
– the additive *Nitrocet 45*, 0.5 %. This additive increased the rape oil cetane index value of about 15 units.

Vegetable oils are characterized by a run of the distillation curve different from this of the gas oil. It means, among other things, higher temperatures at the beginning of the distillation and impossibility of full evaporating of the fuel. Higher temperatures lead to a thermal cracking [6], which is the cause of important amounts of deposit on the atomizer and in the combustion chamber. This was the reason to use a commercial washing additive “Kleen-flo”, very effective for the rapeseed oil. It was confirmed also by our other tests.

The rapeseed oil has considerably lower value of the cetane index than the gas oil (Tab.1). It usually causes an increase of the self-ignition delay, higher maximum speed of the combustion pressure growing (just after the self-ignition), higher maximum combustion temperatures, and, in consequence, a rise in emission of nitric oxides NO_X [9, 7]. To reduce such inconveniences, we used the additive increasing the rape oil cetane index value up to the level LC for the gas oil.

3. TEST STAND

During the investigation, the engine Perkins 2806A-E18TAG2, which was the integral part of the generating set, was stopped by changing the electric load of the generator. Main elements of the measuring line used here are connected with the analysis of the energy parameters and toxicity of the exhaust gases. Applied measurement systems were produced by the firm AVL (Austria). Here are some of them:

- computer mass fuel gauge, produced by AVL
- measurement system to determine the concentration of the exhaust gaseous components - AVL Bench Emissions System CEB II (O_2 – PMD, CO, CO_2 – NDIR, HC – FID, NO_x – CLD)
- Measurements stand with the exhaust gas diluting tunnel and computer microbalance of Sartorius (measurement accuracy – 0.001 mg) to determine the emission of the particulate matters in the engine exhaust gas.
- measurement stand to determine the smokiness level in Bosch scale – AVL Smoke Meter
- Measurement stand to determine: exhaust gas temperature, ambient temperature, pressure and humidity of the air absorbed by the engine, excess air factor λ.

Exhaust gas toxic components were measured using the apparatus in accordance with the binding standards: ISO/CD 8178-1 (RIC engines-Exhaust emissions measurement, edition 11.XI.1992) and ECE – R49/2(Uniform provisions concerning the approval of compression ignition (C.I.) engines and vehicles equipped with C.I. engines with regard to the emissions of pollutants by the engine).

4. INVESTIGATION RESULTS AND THEIR ANALYSIS

As mentioned above, the measurements were performed at the constant engine speed of 1500 rpm and at the loading of the generating set electric power 0 to 480 kW. For each of the examined fuels (gas oil, rapeseed oil), 13 measurement points of energy and ecology engine parameters have been done. Loading changes of the combustion engine (Perkins 2806A-E18TAG2), being an integral part of the generating set, were done using an electric engine dynamometer of the maximum power 500 kW.

The principal energy parameter considered in the analysis of the rape oil effect as compared with the gas oil, is the Gp fuel consumption per hour [kg/h]. The results are showed on the Fig. 1. It is visible, that supplying the examined Diesel with the rape oil causes the increase of the fuel consumption per hour, rising when the engine load grows. At 480 kW of the received electric power, the increase of the fuel consumption, in the case of rape oil supply (as compared with the gas oil) comes to 20 %. It is however to notice, that the rapeseed oil density (ρ=0.913 g/cm^3) is significantly higher than this of the gas oil (ρ=0.825 g/cm^3). For that reason, after the recalculation of the fuel consumption from the mass units (kg) to the volume units (dm^3), the increase of the fuel consumption – of the rape oil – in comparison with the gas oil, is only about 8 %. Also, we have to take into consideration the fact, that the rape oil calorific value (38.0 MJ/kg and 34.5 MJ/dm^3) is lower than this of the gas oil (42.6 MJ/kg and 35.2 MJ/dm^3). Then, if the differences in calorific values of the examined fuels were considered, the overall efficiency of the examined engine for the rape oil would be practically on the same value level, than for the gas oil.

The last important conclusion resulting from the analysis of data showed on the Fig. 1, relating to the Gp fuel consumption per hour for the gas oil and rapeseed oil (at a constant rotational speed of the engine n = 1500 rpm and changing load) concerns the measurements scatters. The diagram shows clearly that the rapeseed oil is characterized by the higher lack of repeatability of the fuel consumption per hour than the gas oil (measurements done 3 times, on different days for each fuel), which is an important advantage. It results from the fact that the vegetable oil is characterized by a larger fluctuation of the processes: injection, atomization, evaporation, mixing with the air, self-ignition and finally – combustion process itself. However, from the point of view of the engine (generating set) user, it is not very important, because mean values are significant only in a long time.

Changes of Gp fuel consumption per hour involve changes of excess air factor λ. The values λ for both examined fuels are practically the same within the whole range of engine load. Some small changes – slightly lower values of λ for the vegetable oil – are due both to the higher fuel consumption (rapeseed oil) and to the differences in values of stoichiometric constant Lt coming to about 14.5 kg air/kg fuel for the gas oil and about 12.5 kg air/kg fuel for the rapeseed oil. The constant stoichiometric values are dependent on the elementary composition of the fuel (fuel constant), i.e. on the amount of carbon/hydrogen/oxygen/sulphur in the fuel. In principle, the amount of the sulphur in the fuel (in compliance with the European Fuel Card) is so small – 50 ppm for the gas oil – that there is no need to consider it in Lt calculation for the rapeseed oil. In the case of rapeseed oil, the situation is even more favourable, because vegetable oils, practically, do not contain the sulphur. In the conventional gas oil, there are no oxygen molecules (mixture of different hydrocarbons). The advantageous feature of the rapeseed oil is the fact that this fuel contains about 10 % of oxygen in its particle. It is favourable for the optimization of the combustion process run, disturbed otherwise, as compared with the gas oil, by a significantly higher value of viscosity, density, surface tension, distillation curve run etc., as compared with the gas oil.

The changes of the air excess factor are usually accompanied by the changes of the exhaust gas temperature. In accordance with the statement above, the change of the examined engine supply system from gas oil to rapeseed oil, without significantly changing the air excess factor value, in spite of a small increase of the fuel consumption, does not influence the exhaust gas temperature. It is important, because it indicates a similar situation of the combustion process for the rapeseed oil as for the gas oil. If the vegetable oil combustion happened disadvantageously too late (relative to the top dead centre) in the case of the rapeseed oil as compared with the gas oil, which would deteriorate the combustion efficiency, the exhaust gas temperatures would be showed as higher. The test results presented on the Fig. 2 show, that in the case of this particular supply system of a Diesel, equipped with the injection units, the rapeseed oil supply does not cause a delayed combustion. It is importantly due to the high maximum fuel pressures, which equalizes partly the negative effect of the high viscosity of the rape oil in the process of injection and atomization of such a fuel on its combustion and enables a good preparation of the mixture rapeseed oil-air, ensuring the similar time and situation of the combustion process as for the gas oil.

The results of measuring the concentration of the nitric oxides NO_X in the exhaust gases, for the examined fuels, are presented on the Fig. 3. The data on the diagram indicate that the application of the rapeseed oil supply in a Diesel causes an increase of the nitric oxides concentration at higher loads (above 128 kW), as compared to the gas oil supply. Probably, this range of the generating set loading will be realized most often in practice. At maximum engine loads, the increase of the NO_X concentration in the exhaust gas comes to about 18 %. This tendency maintains within 250 to 480 kW of the electric power developed by the combustion engine. It is important, because the nitric oxides NO_X are the most toxic of the exhaust gas components. It must be however noticed, that the NO_X forming is due to the maximum combustion temperatures (so called "maximum maximorum of the temperature") appearing locally and temporarily in the combustion chamber. If there were no application, in the case of the rape oil, of the additive ("Nitrocet" or any other increasing the cetane index value), the concentrations of NO_X in the exhaust gases would be certainly higher. It results from the fact that the crude rape oil has significantly lower cetane index value than the gas oil. In this case, a lower value of the cetane index causes a reduction of the vegetable oil tendency to self-ignition. In consequence, the time between the beginning of the fuel injection (of the rape oil as compared with the gas oil) and the beginning of the self-ignition is longer. In this longer time – between the beginning of the injection and the beginning of the self-ignition – in the combustion chamber gathers a great amount of the fuel supplied by the injection units. A greater fuel mass in the combustion chamber, gathered before the self-ignition, in the moment of the fuel (rape oil) ignition, ignites incomparably more violently (explodes) than the gas oil. It results in increasing the values: of maximum combustion pressure, maximum speed of the combustion pressure growing (dp/dα) max, "hardness of engine operation", maximum combustion temperature and of NO_X concentration [7, 9]. The additive "Nitrocet", raising the cetane index value and increasing by this the tendency of the rape oil to self-ignition, equalizes considerably these problems. Paradoxically, it is also important that the application of a modern Diesel, equipped with the injection system with very high maximum pressures of the fuel injection, improves the processes of the rape oil injection and atomization reducing the fuel consumption – of the rape oil), but on the other hand, it enlarge, in the determined time of the self-ignition delay τ_S, the amount of the fuel in the combustion chamber, in the time between the beginning of the injection and the beginning of the self-ignition, which increases the maximum speed of kinetic combustion and causes higher concentrations of NO_X in the exhaust gases. From this point of view, Diesel engines equipped with traditional injection pumps with lower maximum pressures of the fuel injection, turn out to be a little more advantageous, though the engines with such supply systems involve a greater consumption of the fuel.

It must be remembered that, at the values of the air excess factor λ applied in Diesel engines and measured on the examined engine, the application of conventional, in series production, catalytic converters, will reduce only the emission of carbon monoxide CO and of unburned hydrocarbons THC, without lowering the concentration and emission of NO_X in the exhaust gases. To achieve this, some special systems reducing NO_X should be used, as well as the filters of particulate matters for the emission of the application of such NO_X reducers and particulate matter filters with a continuous regeneration (CR) requires further investigations. In the case of generating sets, it is much simpler than in the case of traction engines because of the constant rotational speed of the engine.

The concentration of the carbon monoxide CO in the exhaust gas of the examined Diesel engine, connected with a generator, analysed in relation to the loading, for the gas oil and rapeseed oil, are similar (qualitatively). The test results indicate that the CO concentration values are, at low engine loads, very similar to these of the gas oil. At higher engine loads (above 256 kW), the concentration and the emission CO are lower for the rape oil than for the gas oil. The difference comes to 35 % as related to the gas oil.

A similar tendency is also observed for the concentration (Fig. 5) of unburned hydrocarbons HC. At high engine loadings, the amount of emitted unburned hydrocarbons in exhaust gases is lower for the engine supplied with the rape oil than in the case of the gas oil. It results mainly from the favourable effect of high combustion temperatures (extremely important in the case of the rapeseed oil) on the oxidation of hydrocarbons in the engine cylinder. If there were necessity of reducing carbon monoxide and unburned hydrocarbons emissions, a good solution would be in this case the mass-produced catalytic converter, selected to match the temperatures and rate of the fuels flow.

The effect of growing load of the examined engine on the particulate matter emission (Fig. 6) is quite different. In the case of gas oil, for which the producer optimized the examined engine, the emission of particulate matter changes only slightly. While in the case of the rapeseed oil, an increase in the engine power involves an intense growth of the particulate matter emission. At the full engine loading, the emission of PM is higher for the rape oil even of about 275 % as compared with the gas oil. At the electric power 480 kW, the emission per hour of the particulate matters comes to about 20 g/h for the gas oil and about 75 g/h for the rape oil. Moreover, the test results presented on Fig. 6 show clearly, that the mean standard deviations calculated from 3 repeat measurements of the PM emission are considerably higher for the rape oil than for the gas oil. It is due directly to the larger fluctuations of proportioning the rape oil in relation to the gas oil, which was already mentioned in the analysis of the fuel consumption per hour (Fig. 1).

Unfortunately, no change of the engine control parameters (for instance, the beginning of the fuel injection or/and the supercharging pressure) can be considered as a remedial measure. It is so, because any construction or regulation changes of the engine, reducing the emission of the particulate matters, would cause at the same time an increase of the nitric oxides NO_X emission. This emission is anyway higher for the rape oil than for the gas oil. The only, theoretically possible solution would be shaping the fuel injection characteristic in such a way that the maximum speed of kinetic combustion is reduced in purpose to lower the NO_X emission and raise the maximum speed of diffusion combustion to reduce the emission of PM. It is however impossible in the case of injection pumps. The unique supply system allowing shaping the fuel injection characteristic is the common-rail system. In the case of the examined engine with injection pumps, the only sensible method of reducing the emission of particulate matter would be the application of a particulate matter filter with the continuous regeneration, but such a solution involves considerable expenses.

5. CONCLUSIONS

The investigation of the effect of fuelling a modern Diesel Engine with the crude rapeseed oil allows formulating a few essential conclusions:

1. The work of a Diesel engine on the crude rapeseed oil is possible, which was confirmed by the operation during many months of operating a generating set with the engine Perkins 2806A-E18TAG2 of the power rating 500 kW, but it is necessary to adapt the supply and control systems of such an engine as well as to use appropriate additives to the vegetable oil.
2. The use of the crude rapeseed oil in a modern Diesel high-power engine involves, among other things, an increase of the fuel consumption per hour (at the principally stable values of the engine total efficiency), and the increase of both the nitric oxides concentration and of the particulate matter emission.

The concentrations of the gaseous compounds of the incomplete combustion remain in principle on a similar level as those for the gas oil.

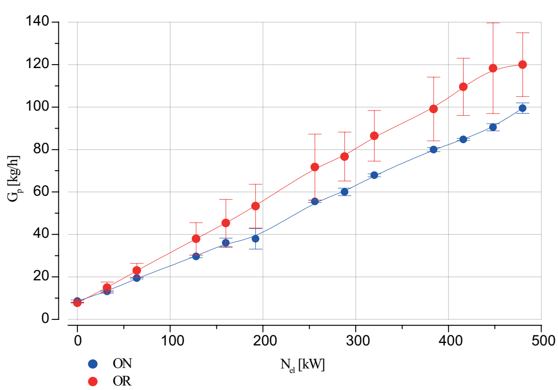

Fig. 1. Consumption per hour in the examined engine for the gas oil and for the rape oil.

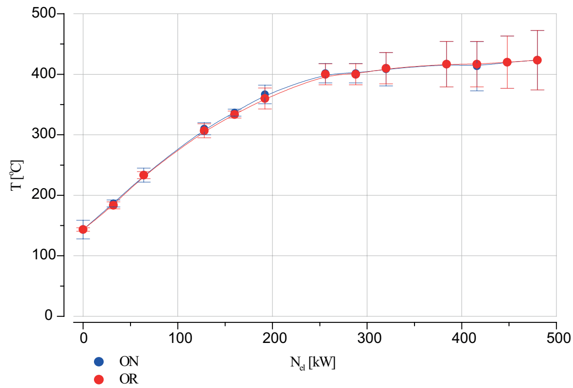

Fig. 2. Exhaust gas temperature in the examined engine for the gas oil and for the rape oil.

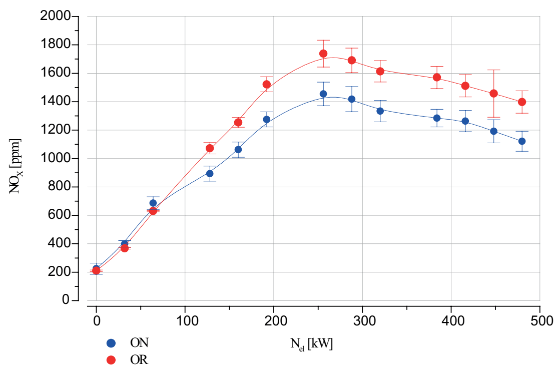

Fig. 3. Concentration of nitric oxides NOx in the engine exhaust gas for the gas oil and for the rape oil

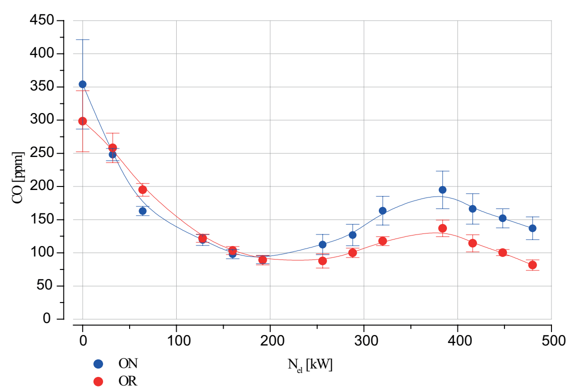

Fig. 4. Concentration of the carbon monoxide CO
in the engine exhaust gas for the gas oil and for the rape oil.

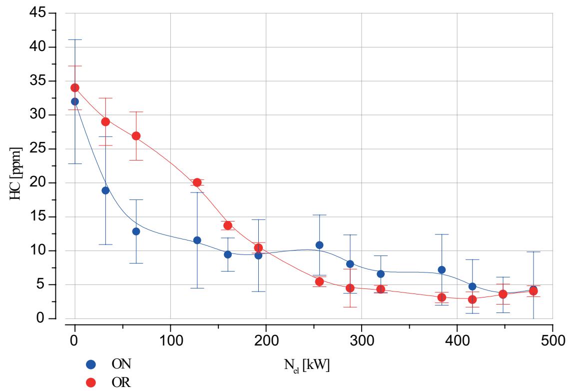

Fig. 5. Concentration of the unburned hydrocarbons in the exhaust gas for the gas oil and for the rape oil.

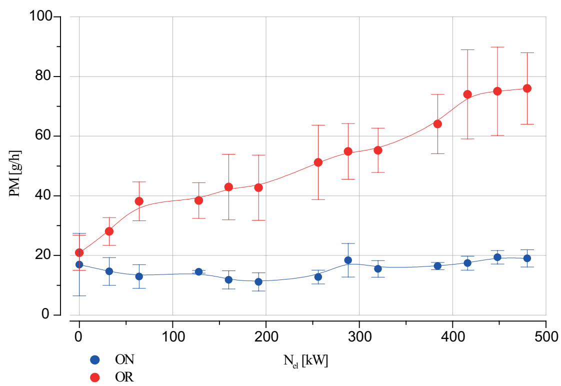

Fig. 6. Emission of particulate matter PM in the exhaust gas for the gas oil and for the rape oil.

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WŁAŚCIWOŚCI SILNIKA DIESLA ZASILANEGO NATURALNYM OLEJEM RZEPAKOWYM

Streszczenie. W artykule przedstawiono wyniki badań silnika diesla o mocy 500 kW zasilanego naturalnym olejem rzepakowym. Podano techniczne aspekty przystosowania silnika do pracy na oleju rzepakowym oraz stosowane dodatki do oleju, pozwalające na bezawaryjną pracę silnika. Mierzono parametry energetyczne i toksyczność spalin. Stosowano metody badań i aparaturę pomiarową zgodną z normami ECE. Ze względu na fakt, że silnik był integralną częścią agregatu prądotwórczego, pomiary przeprowadzono przy stałej prędkości obrotowej n=1500 obr/min. i zmiennych obciążeniach silnika. W wyniku przeprowadzonych badań stwierdzono między innymi, że zastosowanie oleju rzepakowego, w miejsce oleju napędowego, powoduje wzrost godzinowego zużycia paliwa (przy niezmiennych zasadniczo wartościach sprawności ogólnej), wzrost stężenia zarówno tlenków azotu NO_X jak i emisji cząstek stałych (PM).

W konkluzji przeprowadzonych badań można stwierdzić, że istnieje możliwość zasilania silników wysokoprężnych dużej mocy naturalnym olejem rzepakowym, pod warunkiem przystosowania do tego celu zarówno silnika jak i paliwa

Słowa kluczowe: naturalny olej rzepakowy, parametry energetyczne, spaliny, cząstki stałe