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SMOKE EMISSION OF AD3.152 ENGINE FUELLED WITH RAPESEED OIL/DIETHYL ETHER BLENDS

ZADYMIENIE SPALIN SILNIKA AD3.152 ZASILANEGO MIESZANINAMI OLEJU RZEPAKOWEGO I ETERU DIETYLOWEGO

WINCENTY LOTKO[1], ARKADIUSZ HERNIK[2], JERZY STOBIECKI[3], THEODOROS KOSMANIS[4], MILENA GÓRSKA[5]

Kazimierz Pulaski University of Technology and Humanities in Radom,
Alexander Technological Educational Institute of Thessaloniki

Summary

The paper presents research results on smoke emission from AD3.152 diesel engine fuelled with rapeseed oil (RO) and its blends with diethyl ether (DEE). All necessary tests were carried out in stationary condition for selected rotational speeds of the crankshaft i.e. 1000, 1500 and 2000 rpm as well as engine loads of 40, 80 and 120 Nm. Results of the research confirmed, that diethyl ether added in volumetric ratio of 40% to rapeseed oil reduces smoke opacity even by 50% compared with the engine fuelled with neat rapeseed oil.

Keywords: diethyl ether, rapeseed oil, biofuels, renewable fuels, diesel engine

[1] Kazimierz Pulaski University of Technology and Humanities in Radom, Faculty of Mechanical Engineering, ul. Jacka Malczewskiego 29, 26-600 Radom, Poland; e-mail: lotko@uthrad.

[2] Kazimierz Pulaski University of Technology and Humanities in Radom, Faculty of Mechanical Engineering, ul. Jacka Malczewskiego 29, 26-600 Radom, Poland.

[3] Kazimierz Pulaski University of Technology and Humanities in Radom, Faculty of Mechanical Engineering, ul. Jacka Malczewskiego 29, 26-600 Radom, Poland.

[4] Department of Automotive Engineering, Alexander Technological Educational Institute of Thessaloniki, Sindos 574 00, Greece.

[5] Kazimierz Pulaski University of Technology and Humanities in Radom, Faculty of Materials Science, Technology and Design, ul. Jacka Malczewskiego 29, 26-600 Radom, Poland.

Streszczenie

W artykule przedstawiono wyniki badań zadymienia spalin silnika o zapłonie samoczynnym AD3.152 zasilanego olejem rzepakowym (OR)oraz jego mieszaninami z eterem dietylowym (DEE). Wszystkie niezbędne badania wykonano w warunkach ustalonych dla wybranych prędkości obrotowych wału korbowego tj. 1000, 1500 i 2000 obr/min oraz obciążeń 40, 80 i 120 Nm. Uzyskane wyniki potwierdzają, że dodatek eteru dietylowego w objętości 40% do oleju rzepakowego zmniejsza zadymienie spalin nawet o ok. 50% w stosunku do silnika zasilanego olejem rzepakowym.

Słowa kluczowe: eter dietylowy, olej rzepakowy, biopaliwa, odnawialne paliwa, silnik diesla

Introduction

Having analyzed the current trends in the development of vehicle propulsion, one cannot fail to notice the ever so strongly emphasized aspect of the environmental performance of Combustion engines are almost universally fueled with refined petroleum products, i.e. fuels obtained from non-renewable sources. While vehicle manufacturers strive to meet the ever more stringent vehicle emission standards for limited exhaust emissions, noise emission and smoke opacity, all the interventions and efforts aim at either mitigating or eliminating the negative impact on the natural environment made by conventional internal combustion engines.

Both construction and research works of large corporations, but also independent research units, concentrate on two domains related to the development of vehicle propulsion in response to the expectations of the modern automotive market. The first domain aims to develop an alternative vehicle motor, not by modifying the internal combustion engine, still archaic in its design, even if continuously improved, but by adapting technology different from the conventional motor. Examples of such solutions include electric vehicles using the battery power supply, the ability to quickly charge batteries, even wirelessly, the wireless "traction" power network, recuperation of energy through super capacitors, photovoltaic cells, etc. The second much more developed way to meet the ever more stringent requirements is to adapt the conventional power supply system so that it can be supplied with fuels of lower toxicity. Among such solutions, the well-researched formulas include: gas derived from refining crude oil, natural gas in various forms, vegetable oil fuels and their esters as well as alcohol and ether compounds [3, 6, 7, 10].

1. Literature review

Supplying engines with fuels based on vegetable oils is hardly a new idea. When in the last decade of the 19th century Rudolf Diesel was developing his compression-ignition engine, he adapted it to be supplied with mineral oil and peanut oil. For decades, plant fuels have not been fully appreciated. The only exceptions were the short periods during the Second World War when fuel shortages on the front lines forced nations to obtain fuels from other sources.

The good control of technologies for mining, processing and distribution of fossil fuels meant that alternative fuels were not perceived as attractive, especially due to their higher costs at that time and relatively worse properties. The situation changed in the seventies of the twentieth century under the influence of the world oil crisis, which affected the highly industrialized countries.

The next fuel crisis arose from 1979 to 1982. It led to a crisis in the global monetary system and the economic crisis accompanied by recession and high inflation. Both events spurred the search for new natural resources, but also rekindled the interest in the concept of alternative fuels. The last significant drop in oil prices was recorded after the first Gulf War. Since then, oil prices have been steadily increasing while the resources are inevitably shrinking.

The work on the use of vegetable oil to power compression-ignition engines, depending on the geographical region, focused on researching of soybean, sunflower, rapeseed, linseed, maize, palm, peanut cotton, sesame and coconut oil. In their chemical nature, vegetable oils are esters of glycerol and fatty acids containing in one molecule even 22 carbon atoms or 14-18 atoms in the case of rapeseed oil. The presence of free fatty acids in the ester class makes vegetable oils susceptible to hydrolysis and esterification. The presence of numerous unsaturated bonds in their molecules promotes their oxidation and polymerization.

Motivated by the production cost, ester is produced with the use of methyl alcohol or, less commonly, ethanol. In Poland and Europe, esters are usually produced using rapeseed oil and methyl alcohol. Methyl esters of higher fatty acids are assigned the acronym FAME (Fatty Acid Methyl Esters), and ethyl esters FAEE (Fatty Acid Ethyl Esters). Methyl esters of higher fatty acids of rapeseed oil are given the symbol RME (Rape-seed Oil Methyl Ester – in Poland often: EMKOR). Currently, in Poland FAME type fuels, in accordance with the standard PN-EN 590, can account for up to 7% of the fuel distributed as diesel oil.

To improve the rape oil combustion process, attempts have been made to mix it with either water or alcohol [1]. Water evaporates rapidly (explosively) in the hot combustion chamber and improves the RO spraying process. As a result, the smoke opacity and the content of nitrogen oxides in the exhaust emission can be reduced. In turn, the application of ethyl alcohol in the RO results in an increase in the ignition delay of such a mixture. Combustion process of such blends occurs with higher value of in-cylinder pressure rise rate.

In addition, the application of ethyl alcohol in the RO reduces the amount of deposits in the combustion chamber in comparison to the engine fuelled with neat RO. Attempts have also been made to apply a mixture of diesel fuel, RME and dehydrated ethyl alcohol, called Bioxdiesel, to the compression-ignition engines. The advantage of this mixture is the improved low temperature propertiesas well as excellent lubricity. This method has produced lower toxicity of exhaust gases although the mixture displays a lower calorific value than diesel fuel (proportional to the share of alcohol and RME in the mixture). This results in a deterioration of the engine performance (at the same fuel dose as diesel fuel) or an increase in fuel consumption when the dose is increased.

Refined petroleum fuels are likely to remain the main fuel source for internal combustion engines for a long time. The introduction of oxygen additives to mineral fuels may have a beneficial effect on the performance of the engine's operating processes and enhance the protection of natural environment against the products of the combustion process. Particularly promising seem to be the additives containing ethanol derivatives and some ether.

Both ethers and ethanol derivatives display no hygroscopic properties which makes them miscible with diesel oil. The mixtures thus obtained are homogeneous, remain stable within a wide range of temperatures and absorb no moisture from the environment. The main advantages of diethyl ether are its high cetane number and good miscibility with both diesel and ethanol. Its main disadvantages, however, include the low combustion temperature of diethyl ether (approximately -40ºC) which requires taking special safety precautions in transporting and refueling.

Sidibe et al. [9] in their study from 2010 indicated many studies on the use of vegetable oils for powering combustion-ignition engines. The previous studies had demonstrated the usefulness of simple vegetable oils (SVO-Straight Vegetable Oil), produced locally, perceived as simple and cheap in production while being environmentally friendly. The research highlighted the different physical and chemical properties of vegetable oils in comparison to diesel oil which may cause some technical problems in the longer use of the so-fueled engines. The study's literature revealed a debate between various authors contesting about the possible consequences of the use of simple oils and possible solutions of potential problems. Current research indicates a reduction in the service life of engines due to the deposition of carbon deposition in the combustion chamber and its spread into the lubrication system. Attempts have been made to counteract this phenomenon for example by heating vegetable oil before injection into the combustion chamber, which has proven ineffective.

Labeckas and Slavinskas [11] conducted a comparative analysis of the compression-ignition engine with direct injection fuelled with either diesel oil or cold-pressed rape oil (RO). The research was focused on the influence of OR fuel on the engine's efficiency and the formation of carbon deposits in the injectors in the transient operating states of the engine.The study showed that a standard OR fueled diesel engine consumes about 12% more fuel at maximum speed, which results from the lower heating value of OR, also recording the smoke opacity reduced by 35%. Facilitating the motor with a fuel heating system with heating capacity of up to 60ºC reduced OR's viscosity, flow resistance moving through injectors and filters, and consequently the possibility of obtaining a fuel consumption higher by 7.5% in comparison to diesel fuel. Further heating to 90ºC failed to bring any measurable effects, and even led to an increased smoke opacity. Again, the researchers observed the problem with the deposition of carbon in the injectors fueled only by OR, carbon-baked piston rings and recommended twice as frequent engine inspections. Using a modified engine in which a number of injectors were powered by pure OR and the others with standard diesel fuel the research proved that the rapid formation of carbon deposits is probably caused by uneven distribution of fuel drops, slow evaporation and lower propensity to combustion-ignition, which in turn leads to incomplete combustion of fuel. This inferior spraying capacity of pure OR may cause an unstable engine operation at the low and medium rotation speed.

An important feature was also the increased corrosion process and the degradation of rubber seals. Further long-term engine-test-stand tests are required to determine the range of the necessary modifications to the fueling system.

Drown at al. [12] focused on the effect on lubricity in the use of ethyl and methyl esters of various vegetable oils using the HFRR method (High Frequency Reciprocating Rig). In their study, they emphasized that ethyl esters clearly improve lubricity compared to methyl esters. In addition, there was no clear correlation between the improvement of lubricity and the fatty acid profile of the ester.

Nazal et al. [13] conducted comprehensive studies on the validity of the use of biodiesel additive – i.e. vegetable oil subjected to the transesterification process in comparison to diesel oil. The tests were carried out on mixtures containing 5, 8 and 11% biodiesel, and tested on a single-cylinder test engine under regular operating conditions. The research showed that pure vegetable oils can be a viable alternative fuel for the CI engine with a standard supply system, but only in a short period of operation. In the case of a long-term use of the CI engine powered by a mixture of diesel oil and vegetable oils, the researchers drew a clear limit line of 20% of vegetable oil content in the mixture, above which severe engine problems were almost unavoidable.

Wang et al. [14] applied a mixture of vegetable oil and diesel fuel to the test engine in the proportions of 25, 50, 75 and 100 percent. The experiment was carried out on the engine at a constant speed of 1500 rpm. The test results were correlated with the values obtained when the engine was powered by diesel oil. The results confirmed the previous theses: although both the power and fuel consumption were comparable with the values obtained in the case of the diesel oil supply, the exhaust emission data looked more promising: significantly lower emission of nitrogen oxides and, at low engine speed, also carbon monoxide.

As early as 1997, Bailey et al. [2] observed that "producing and using renewable fuels for transportation is one approach for a sustainable energy future for the United States, as well as the rest of the world. Renewable fuels may also substantially reduce contributions to global climate change. "The authors forecast the use of ethanol as an alternative fuel for powering vehicles with a combustion-ignition engine. At the same time, they advocated considering the possibility of feeding diesel engines with diethyl ether (DEE), obtained in the ethanol dehydration process, having characterized DEE as a well-known agent supporting cold start. The researchers pointed to the little knowledge about the feasibility of using DEE to power such engines, whether directly in pure form or as part of mixture, in contrast to dimethyl ether (DME), which had been more extensively tested and found applicable as an alternative fuel with low emission levels. The study presented both the validity and economics of obtaining DEE from biomass based ethanol. The comparison of properties in relation to: dimethyl ether, methanol, ethanol, methylal, propane, natural gas (CNG), gasoline, biodiesel, Fischer-Tropsch synthetic gas and diesel oil indicated a high cetane number, low self-ignition temperature, low viscosity, a wide flammability range of the mixture and low boiling point. Importantly, the author pointed to the earlier attempts to use DEE in the years of World War II, DEE-enriched ethanol was used as motor fuel in the face of scarcity of other aviation fuel. The researchers observed that by creating a mixture containing less than 20% DEE it is possible to improve the ethanol properties, especially solving the initial ignition problems.

In 2009, Purushothaman and Nagarajan [8] conducted a series of comparative tests of engines supplied with orange oil (orange peel), a mixture of orange oil and biodiesel and a mixture of orange oil and diethyl ether, with regard to emissions of carbon oxides (CO), hydrocarbons (HC) , nitrogen oxides (NOx) and smoke opacity.

Test engines were spark-ignition engines powered by a mixture of oil and gasoline, and a combustion-ignition engine powered by a dual-fuel system, in which DEE was added to improve the combustion characteristics in a wide range of the engine operations. DEE was applied directly to the intake manifold, because the high volatility enhances rapid evaporation and the formation of a mixture with the air sucked inside. The addition of DEE made it possible to power the engine with plain orange oil, which in its pure form had too high viscosity, low cetane number and a high self-ignition delay. The addition of DEE allows to burn the oil completely, reducing at the same time the temperature of the exhaust which benefited the reduction of NOx emissions while increasing the emission of CO and HC, which can be explained by the higher flame velocity of such a mixture.

Zhang et al. [5] in 2011, undertook research on a modern CI engine, with a common-rail power supply and turbocharging. The test engine was powered by two types of biodiesel and biodiesel mixture from DEE. The comparisons were made in the conditions of a constant engine speed with the rotational speed of the crankshaft of 1,600 and 2,600 rpm and at three speed configurations: 25, 50 and 75%. The study proved that the addition of DEE had a positive effect on the combustion of vegetable oils. With comparable efficiency and fuel consumption, it was possible to reduce NOx emissions at each speed configuration and crankshaft speed. Yet again, attention was drawn to the fact that DEE greatly increased the cetane number of the mixture, and reduced NOx emissions by reducing the temperature of exhaust gases. Positive effects were also observed when increasing the proportion of the DEE additive at higher engine speeds. Both biodiesel and DEE contain much more oxygen and less sulfur than diesel, which translates into low emission of harmful by-products of the combustion process.

Górski and Przedlacki [4] in 2014, assessed the effect of the DEE additive on selected physicochemical properties of diesel oil and ignition delay. The researchers measured the effect of DEE on the change in the calorific value, kinematic viscosity, density, lubricity, cold filter block temperature, cetane number and also miscibility in comparison with diesel oil. The tests were carried out on two combustion-ignition engines, feeding them with mixtures containing 5, 10, 15 and 20% of DEE. No problems were identified concerning the stability of the mixture in a wide temperature range from -20°C to + 10°C. The test was carried out at crankshaft speeds of 1,000, 1,400, 1,800 rpm and two loads of 80 and 120 Nm. Adding DEE to diesel significantly reduces its viscosity. Particularly, a 5% DEE additive reduces viscosity as much as 26%, yet the studies proved that use a mixture containing up to 20% of DEE is safe. The mixture richer than 20% caused problems in starting the engine, affecting a noticeable drop in power, and as a result of significant dilution – leaks in the fuel system.

In one of the latest studies addressing the use of DEE [15], fuel samples which were a mixture of either 80% diesel oil, 15% palm oil and 5% DEE, or 80% diesel, 10% palm oil and 10% DEE, all tested for emissions and combustion characteristics, were used. The authors confirmed the viability of the DEE use as an oxygen component improving both the combustion characteristics of vegetable oils and the previously mentioned physicochemical properties.

2. Methods and research materials

Rapeseed oil and its blends with addition of 10, 20, 30 and 40% of DEE by volume were examined in this paper. Selected physicochemical properties of these fuels are listed in Table 1.

Table 1. Selected physicochemical properties of tested fuels

Parameter	Fuel				
	OR	DEE10	DEE20	DEE30	DEE40
Kinematic viscosity, [mm²/s]	34	17	10	6	3
Density, [g/cm³]	0,92	0,90	0,88	0,87	0,85
Surface tension, [mN/m]	46	41	37	31	27
Flash point, [ºC]	-	20	-2	-12	-21
Lower heating value, [MJ/kg]	37	36	36	36	36
DEE content in RO, [%, v/v]	-	10	20	30	40

Ether (diethyl ether) is an organic chemical compound in the ether class. It is composed of two ethyl groups attached to an oxygen atom. It is a derivative of alcohols or phenols and an extremely flammable liquid with a flash point of -45ºC and a self-combustion temperature of 180ºC. It is obtained in the process of dehydration of ethyl alcohol. The main advantage of diethyl ether as a fuel additive is its high cetane number, good miscibility with diesel oil, ethanol and vegetable oils, as well as the stability of the mixture.

Rapeseed oil is characterized by a higher viscosity in relation to diesel oil. This usually has a negative effect on the quality of fuel atomization and, consequently, on the deterioration of the quality of the combustion process. However, the addition of DEE to RO significantly reduces the viscosity of such blend. Therefore, it can be expected that the addition of DEE to RO will help to reduce smoke opacity. Also lower surface tension and density of RO with the addition of DEE should improve the quality of the injection process and at the same time improve the process of combustion fuel.

In tests, the AD3.152 engine equipped with a conventional fuel injection system, i.e. a DPA in-line pump and multi-hole fuel injectors was used. Selected technical data of the tested engine is presented in Table 2.

Table 2. Selected technical data of AD3.152 engine

Parameter	Value
Cylinder number	3
Engine capacity	2502 cm^3
Compression ratio	16.5
Maximum power	34.6 kW at 2150 rpm
Maximum torque	145 Nm at 1200 rpm
idle run	750 rpm
Fuel injection system	Lucas - CAV type DPA
Injection delay	17 ^{o}CA before TDC (at idle run)
Injection pressure	17.5 MPa
Injector type	multihole (WZM Warszawa)

Analysis of smoke emission of the AD3.152 engine fuelled with tested fuels was carried out on the test stand showed in Fig. 1.Tested engine (2) was connected to engine brake (3). Parameters of engine work were controlled by steering box (4) and PC work station (5). The AVL 465 gas analyzer (1) was used for measurementsof smoke opacity. Tests were carried out for 1000, 1500 and 2000 rpm as well as for engine loads of 40, 80 and 120 Nm.

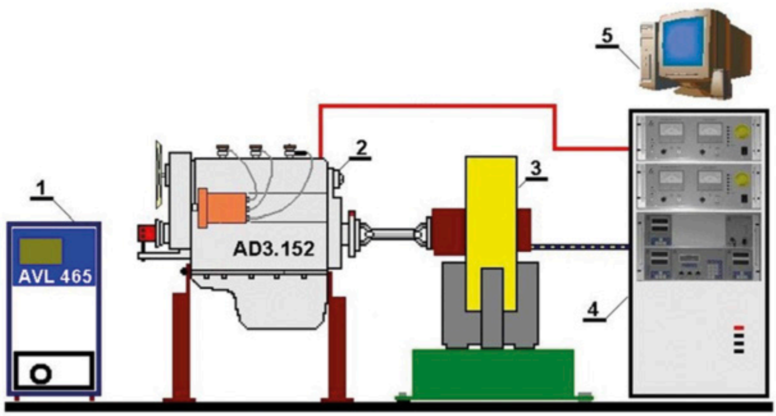

Fig. 1. Test stand scheme: 1 – AVL465 gas analyzer, 2 – AD3.152 engine, 3 – engine brake, 4 – steering box, 5 – PC workstation

3. Research results

Fig. 2 presents variations of smoke opacity of AD3.152 engine operated at 1000 rpm. The engine was fuelled with RO and its blends with DEE.

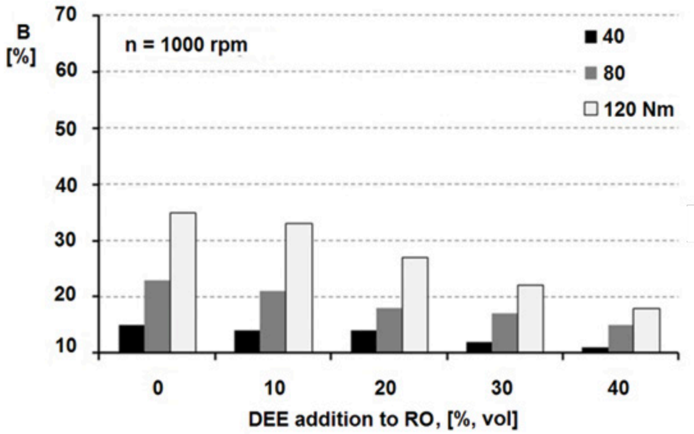

Fig. 2. Impact of DEE addition to RO on smoke emission of AD3.152 engine operated at 1000 rpm

As can be concluded from Fig. 2, the addition of DEE causes a significant reduction in smoke emission of the AD3.152 engine. The largest value of smoke opacity was obtained for the engine operating at the highest load, which results from the larger volume of fuel burned. In this case, the smoke value of the AD3.152 engine fueled with DEE40 fuel was approx. 50% lower in relation to the RO.

Fig. 3 shows the results of exhaust opacity of the AD3.152 engine operating at 1500 rpm. The obtained smoke opacity was higher in relation to the values obtained at 1000 rpm. This is due to the higher exhaust gas flow through the exhaust system. A positive effect of DEE on reducing the exhaust smoke of the tested engine can be found. This was particularly evident for a load of 120 Nm. In this case, the smokiness of the exhaust which was obtained by burning the DEE40 fuel was about 45% lower in relation to the OR.

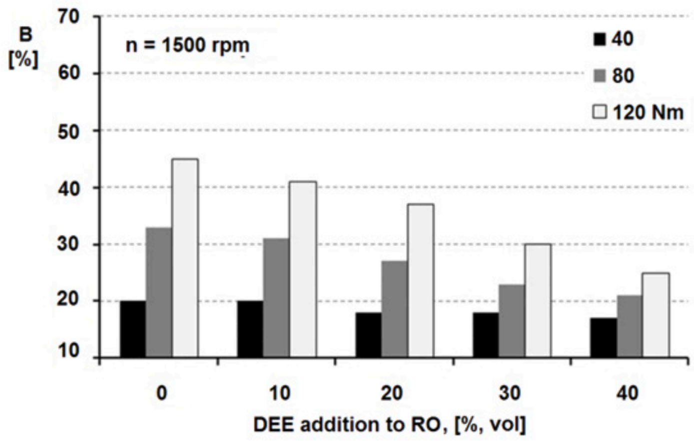

Fig. 3. Impact of DEE addition to RO on smoke emission of AD3.152 engine operated at 1500 rpm

Further increasing the engine crankshaft speed tends to increase smoke opacity due to the higher concentration of the smoke particles in the exhaust gases stream.

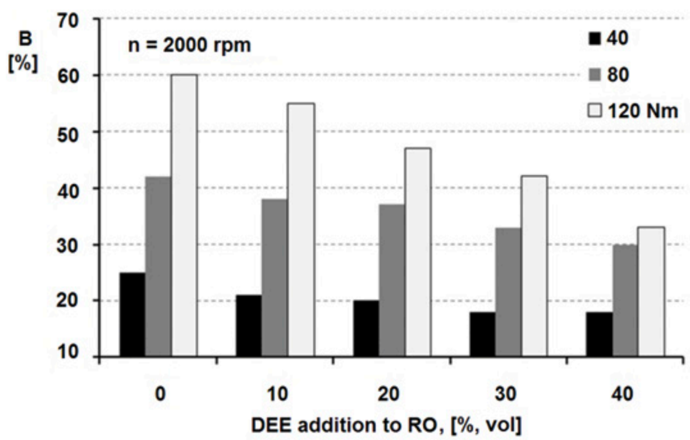

Fig. 4. Impact of DEE addition to RO on smoke emission of AD3.152 engine operated at 2000 rpm.

Based on the analysis of Fig. 4, it can be concluded that the smoke emission of the engine running at the speed of n = 2000 rpm is significantly higher than the results obtained at the speed of 1000 rpm. Nevertheless, it was noticed that the DEE additive reduces the exhaust smoke of the engine operating at all tested load conditions. Particularly beneficial results have been obtained for an engine operating at a load of 120 Nm. In this case, engine smoke opacity was approx. 44% lower compared to RO.

4. Recapitulation

DEE can be blended with RO. Physicochemical properties of these blends are similar to DF. DEE allows to reduce kinematic viscosity, surface tension and density of RO. In this way the quality of fuel injection and combustion process should be improved. Taking this into account, this paper presents results of smoke emission from diesel engine fuelled with RO and its blends with addition of 10, 20, 30 and 40% by vol. of DEE. Tests were carried out for low, middle and higher rotational speeds of the crankshaft and for low, middle and higher load of the tested engine. Obtained results confirm that DEE blended with RO allows the reduction of smoke emission even by 50% compared to the values obtained for the same engine fuelled with neat RO.

The full text of the article is available in Polish online on the website http://archiwummotoryzacji.pl.

Tekst artykułu w polskiej wersji językowej dostępny jest na stronie http://archiwummotoryzacji.pl.

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