

Keywords: biodiesel; fuel blending; exhaust emissions; common-rail; engine efficiency

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EMISSIONS FROM A MEDIUM-DUTY CRDI ENGINE FUELLED WITH DIESEL–BIODIESEL BLENDS

Summary. In the present work, biofuels produced from different raw fatty materials have been proposed as a dominant fuel component in biodiesel–diesel fuel blends. Biofuels were produced from pork lard and rapeseed oil by alkali transesterification using methyl alcohol. Blends of biofuels in volumetric proportions of 60 and 80% of the biocomponent and the remaining part of the conventional fuel were used in a compression ignition engine designed for medium-duty vehicles. The experiments were conducted at two engine rotational speeds (1500 and 3000 rpm, respectively) and a set of load conditions (50, 100, and 200 Nm, respectively). The tests focused on engine efficiency parameters (brake-specific fuel consumption and brake fuel conversion efficiency) as well as exhaust gas emissions (hydrocarbons, carbon monoxide, and carbon dioxide were determined). The obtained results indicate that blends containing biocomponents produced from pork lard were characterized by superior fuel consumption and efficiency results, compared to blends containing biocomponents produced from rapeseed oil. In terms of exhaust emissions, biocomponents produced from pork lard were also characterized by lower emission of all of the examined components compared to rapeseed methyl ester–diesel blends. This study proposes that fuel components obtained from custom (animal) raw-fatty material can be an effective substitute for commonly used rapeseed oil methyl esters.

1. INTRODUCTION

Combustion engines are gradually being replaced by electric motors, in particular, in passenger cars. The aim of switching from hydrocarbon fuels to electricity is to locally reduce toxic emissions that are produced during the fuel combustion process. These trends can be attributed to growing levels of environmental awareness in modern societies as well as the adverse health effects of exposure to fuel combustion products observed in humans and other living organisms [1-5].

Measures that aim to reduce exhaust gas emissions through the replacement of vehicles with internal combustion engines to electric and hybrid drivetrains are justified locally, but the full potential of electric vehicles cannot be harnessed during long-distance travel due to significant limitations

associated with long charging times, energy storage density, driving range, etc. Due to a longer uninterrupted travel distance and a well-developed logistics infrastructure, vehicles with conventional (internal combustion) engines powered by hydrocarbon fuels are presently unrivaled in the transport of passengers and goods across distances longer than 300 km [6]. Currently, two approaches to reconciling environmental and logistic concerns are being developed. In the first one, continuous improvements in engine control and design are being made to optimize the combustion process. This approach also focuses on the advancement of exhaust aftertreatment technology [7]. The second approach is focused on the reduction of the harmful impact of exhausts on the environment by promoting the use of renewable fuel components [7-8]. In terms of the technical aspects, the vast majority of medium- or heavy-duty vehicles are equipped with compression-ignition engines, which are characterized by superior performance and lower fuel consumption than spark-ignition engines. Another advantage of compression-ignition engines is that conventional (fossil) fuels can be relatively easily replaced by alternative equivalents [9]. Also, widespread and popular in the design of compression ignition engines is the Common-Rail injection system, which provides full flexibility of injection control in terms of timing, duration, and injection pressure; hence, the use of alternative fuel components, in the vast majority of cases, does not require any additional changes in the engine design or fuel supply [10-12].

2. ALTERNATIVE FUELS FOR CI ENGINES

Fuels produced from renewable resources contribute to socially acceptable phasing out of fossil fuels and diversification of energy sources that can completely or partly replace non-renewable energy carriers. Unlike fossil fuels, renewable fuels are carbon-neutral and do not exert a negative impact on the environment. Biofuels produced from waste materials should also be considered as economically viable and ethical sources of energy.

Biofuels produced from vegetable oils, animal fats, or waste fatty-materials have physicochemical properties similar to those of conventional diesel fuel; therefore, they can be treated as its substitute. However, even minor differences in fuel properties [13-14] can induce significant variations in the combustion process, or safety of use. The type of raw material used for biodiesel production influences the properties of the final product [15-17]. However, biofuels with suboptimal physicochemical parameters can be used as biocomponents (components of fuel blends) with conventional diesel fuel used to power compression-ignition engines. Biofuels derived from any plant or animal feedstock can be mixed unlimitedly among themselves as well as conventional diesel fuel; thus, the quality of the final fuel and the percentages of renewable components in the fuel blend can be modified to meet user expectations. Biofuels also have other advantages over conventional fossil diesel fuel: they are biodegradable, non-toxic, and characterized by a high flash point, which decreases flammability and the risk of explosion.

Biofuels produced from waste materials are not only economically viable but they also exert a much smaller impact on the natural environment. At present, biodiesel is produced mainly from plant materials, whereas the use of other potential feedstocks, including animal fats, remains limited [18-19]. In Europe, biofuels are produced mainly from rapeseed oil. Rapeseed oil methyl esters are added to conventional diesel fuel sold at petrol stations. The widespread popularity of biodiesel derived from rapeseed oil can be attributed to high and stable rapeseed yields, a relatively simple production process, and the satisfactory quality of the final product [20-23]. Animal fat is also gaining popularity as a resource for biodiesel production.

In the European Union, annual biodiesel production increased from around 0.7 million tons at the beginning of the 21st century to 9.5 million tons in 2011, and it is estimated at 15.5 million tons in 2020 [24-25]. Due to the rapid development of the biofuel industry, the EU has emerged as a major producer and consumer of biodiesel. Poland's national biofuel policy is based on EU regulations and National Indicative Targets (NIT), which specify the minimum percentages of biofuels and other renewable fuels in the total amount of liquid fuel. The NIT has been set at 8.5% for 2020 [26].

The performance of engines powered by biodiesel blends and the proportions of various compounds in biodiesel exhaust emissions are influenced by numerous factors. Engine parameters such as displacement, number of cylinders, and type of fuel injection system can induce significant differences in performance and exhaust emissions. However, it has been proven that fuels containing even small amounts of biofuels are likely to reduce exhaust emissions, even despite the fact that their application may increase the overall fuel consumption [27-32]. Animal-based renewables improve the thermal efficiency of engines and increase pressure inside the combustion chamber, which indicates that biofuels made from animal feedstocks enhance the combustion process [33].

Research into the use of animal fats in the production of biodiesel contributes to the search for alternative sources of energy that can effectively replace fossil fuels. However, most experiments involve single-cylinder engines with outdated fuel injection systems. These types of engines are suitable for preliminary studies, but the obtained results should be validated on conventional engines used on the roads. There is also a general scarcity of published research into biodiesel blends with a high proportion of renewable components.

In view of the above, the aim of this study was to evaluate the influence of biodiesel blends with a high content of renewable components on engine performance and exhaust gas emissions from a four-cylinder CRDI engine designed for medium-duty vehicles.

3. MATERIALS AND METHODS

The influence of fuel blends containing renewable components derived from pork lard on the performance of a compression ignition engine was analyzed. Blends containing identical proportions of biocomponents derived from rapeseed oil were also used during the experiments to verify the effect of the analyzed animal feedstocks on engine performance and emissions.

Biofuels were produced by the alkali transesterification of animal fat and vegetable oil using methyl alcohol. After production, biofuels were combined with diesel fuel to obtain blends containing 60% and 80% of the renewable components in the mixture (by volume). Blends containing plant-based components were labeled RD60 (a mixture of rapeseed oil methyl esters and diesel fuel containing 60% of renewable components) and RD80 (a mixture of rapeseed oil methyl esters and diesel fuel containing 80% of renewable components). Biodiesel blends containing biocomponents derived from pork lard and diesel fuel in identical proportions, as the blends mentioned above, were labeled LD60 and LD80, respectively. Diesel fuel was purchased from a petrol station, and it was also used in engine tests. The results obtained from the analyzed biodiesel blends were compared with the results obtained from diesel fuel. The basic physicochemical parameters of the fuels, presented in Table 1, were examined according to the PN-EN 14214 standard.

Table 1
Physicochemical properties of the analyzed fuels

Sample	RD60	RD80	LD60	LD80	Diesel
Density at 15°C [kg/m ³]	851	863	847	858	824
Viscosity at 40°C [mm ² /s]	3.52	3.89	3.59	3.92	2.78
Sulfur content [mg/kg]	4.09	3.77	2.74	2.31	5.58
Water content [mg/kg]	162	200	242	410	66
Flash point [°C]	66	79	71	80	56
CFPP [°C]	-12	-10	1	4	-12

The experiments were conducted on a four-cylinder ADCR engine with a capacity of 2636 cm³, a maximum torque of 250 Nm, and a rotational speed of 1800-2200 rpm (rated power of 85 kW at 3700 rpm). The engine was designed and manufactured by Andoria-Mot in Andrychów for use in medium-duty/off-road vehicles manufactured in Poland (Honker and Lublin) and Russia (Gazela). The engine was equipped with a Bosch Common Rail CR 2.0 fuel injection system. During

the experiments, the engine's performance was controlled by the (standard) Bosch EDC 16C39 control unit with control algorithms optimized for diesel fuel operation.

The test stand comprised the engine, an AVL DynoPerform 240 dynamometer, and an AVL THA100 throttle actuator for controlling the engine's rotational speed. The remaining test stand components for measuring engine performance, controlling the test stand, and acquiring data were also provided by AVL. Figure 1 presents the schematic diagram of the test stand. The concentration of exhaust gases was measured using the AVL AMA i60 emission bench; the list of examined components and the accuracy of the measurements are presented in Table 2. After the engine's operation was stabilized under the desired experimental conditions, the measurements were performed and all necessary data were read and recorded. The measurement interval was 120 seconds, during which the exhaust analyzers determined the concentrations of individual components. The exact values were registered every 100 ms, and the average values from each measurement interval were used in further analyses. The concentrations of exhaust gases were converted into emission rates using the procedure described in [34]. The air-fuel ratios (λ s) presented in Tables 3 and 4 were calculated with respect to the values for biodiesel (12.5:1) and diesel (14.5:1) and approximated taking into account the percentage of each component in a specified mixture [35]. The set of directly measured engine parameters was used for calculation of the two efficiency parameters: brake-specific fuel consumption and brake fuel conversion efficiency. The detailed descriptions of the test stand as well as the methodology of the measurement and calculation of the analyzed parameters have been reported previously in [36-38].

Table 2

Accuracy of exhaust emission measurements

Parameter	Symbol	Accuracy of measurement	Unit
Hydrocarbon concentration	THC	± 11	ppm
Carbon monoxide concentration	CO	± 13	ppm
Carbon dioxide concentration	CO ₂	± 1	ppt

Engine tests were conducted at two rotational speeds: $n = 1500$ and 3000 rpm. At lower engine speed, for all examined fuel blends, a multiple fuel injection strategy was introduced: during each cycle, the fuel dose was divided into the pilot and the main dose. At higher engine speed, a single dose of fuel was introduced into the combustion chamber during each cycle. At both operational speeds, the engine was subjected to loads of 50 Nm, 100 Nm, and 200 Nm.

4. RESULTS AND DISCUSSION

The results of the engine tests are presented in the subsections of this paper. The first subsection focuses on the parameters of engine performance and efficiency. The emissions of specific exhaust components are presented in subsequent subsections.

4.1. Fuel consumption and engine efficiency

Engine performances at 1500 and 3000 rpm are presented in Tables 3 and 4, respectively.

Specific fuel consumption generally decreased (fuel efficiency increased) with an increase in engine load for all tested fuel blends. This is a well-known phenomenon that can be explained by the changes in the proportions of energy required to generate power and overcome mechanical friction losses.

The analysis of specific fuel consumption and efficiency also revealed that the differences between biodiesel blends and diesel fuel increased with an increase in the engine load. The observed differences were greater at an engine speed of 3000 rpm than 1500 rpm. The highest differences in

fuel conversion efficiency were noted for the RD80 blend (under the highest load conditions); these were, respectively, 1.7% and 3.0% lower than the values for diesel fuel obtained at 1500 rpm and 3000 rpm.

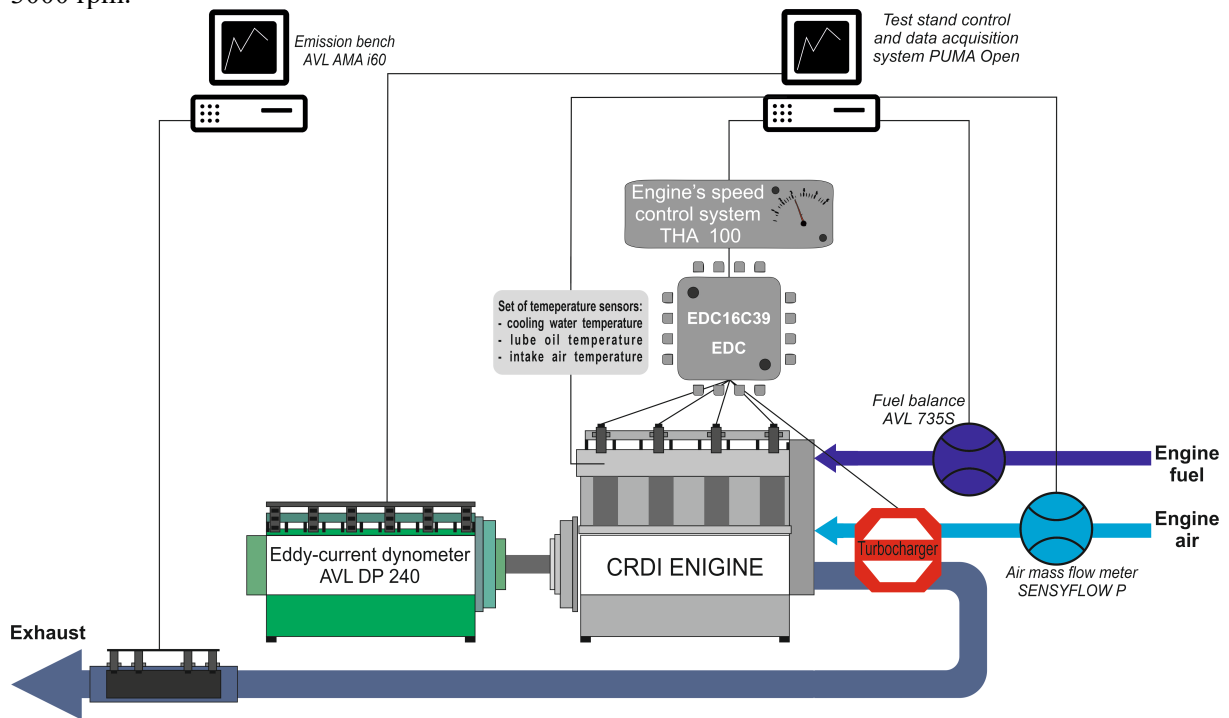


Fig. 1. Schematic diagram of the test stand

Table 3

Engine performance at 1500 rpm

Fuel blend	Engine load	Brake mean effective pressure	Air/Fuel ratio (λ)	Brake-specific fuel consumption	Brake fuel conversion efficiency
	[N m]		[MPa]		
LD80	50	0.24	2.45	367.1	23.6
LD60			2.34	360.6	23.2
RD80			2.55	365.9	23.1
RD60			2.54	358.1	23.0
Diesel			2.54	341.8	22.9
LD80	100	0.48	1.89	305.7	28.3
LD60			1.78	293.0	28.6
RD80			1.80	301.4	28.0
RD60			1.77	299.4	27.5
Diesel			1.71	273.9	28.6
LD80	200	0.95	1.53	267.5	32.3
LD60			1.52	258.1	32.5
RD80			1.55	264.3	31.9
RD60			1.54	258.0	32.0
Diesel			1.56	232.5	33.7

Fuel consumption and conversion efficiency are mostly determined by the calorific value of the individual components in the blend; thus, the type and percentage of biocomponent seem to be the most significant factors influencing the discussed parameters. Diesel fuel has a calorific value of 45.9 MJ/kg [32], while the calorific values of pork lard methyl esters and rapeseed oil methyl esters are 40.1 MJ/kg and 41.6 MJ/kg, respectively (based on the literature data) [39]. These data clearly indicate why diesel fuel has the most desirable values of fuel consumption and efficiency.

However, significant differences were observed between blends with identical proportions of renewable components derived from various feedstocks. Blends containing biocomponents derived from pork lard were characterized by higher fuel conversion efficiency under all experimental conditions than blends containing equivalent proportions of biocomponents derived from rapeseed oil. The above could suggest that biofuels made from animal feedstocks are more effectively converted into usable heat during the combustion process.

Table 4

Engine performance at 3000 rpm

Fuel blend	Engine load	Brake mean effective pressure	Air/Fuel ratio (λ)	Brake-specific fuel consumption	Brake fuel conversion efficiency
	[N m]	[MPa]	-	[g/kW h]	[%]
LD80	50	0.24	2.01	477.7	18.1
LD60			1.91	465.0	18.0
RD80			1.95	477.7	17.7
RD60			1.91	471.3	17.5
Diesel			1.82	452.2	17.3
LD80	100	0.48	1.88	343.9	25.2
LD60			1.86	337.6	24.8
RD80			1.89	343.9	24.6
RD60			1.88	334.4	24.6
Diesel			1.82	289.8	27.1
LD80	200	0.95	1.50	316.9	27.3
LD60			1.48	301.0	27.8
RD80			1.50	315.3	26.8
RD60			1.48	304.1	27.1
Diesel			1.38	262.7	29.9

The operation of the fuel injection system can also contribute to the above differences. When the engine required large doses of less calorific fuel (high rotational speed and high load conditions), the precision of fuel injection naturally decreased; this phenomenon probably contributed to the observed differences in conversion efficiency between specific fuel blends. This observation validates the results of engine tests conducted under the lowest load (50 Nm). Under these operating conditions, when small amounts of fuel were introduced into the combustion chamber, all blends containing renewable components were characterized by higher fuel conversion efficiency (and lower specific consumption) than diesel fuel. Under the discussed engine operating conditions, blends containing biocomponents derived from pork lard were also characterized by higher conversion efficiency, compared to those produced from rapeseed; this phenomenon provides further evidence that animal fat may be more effectively converted into usable heat than plant-based renewables.

4.2. Emissions of exhaust gases

The concentrations of toxic compounds in exhaust gas emissions are presented in Figs. 2-4.

At 3000 rpm and 200 Nm, THC emissions increased (Fig. 2b) and CO emissions decreased (Fig. 3b) in all analyzed fuel blends, relative to diesel fuel. A reverse relationship was observed at 1500 rpm and 200 Nm, when THC emissions decreased (Fig. 2a) and CO emissions increased (Fig. 3a). These results may indicate that, compared to diesel fuel, all analyzed fuel blends were prone to more complete combustion under higher engine rotational speed. Out of all the examined fuel blends, the best results were noted for LD80 (Figs. 2 and 3).

Under moderate engine load conditions (100 Nm), biodiesel blends were characterized by somewhat lower THC (Fig. 2) and CO (Fig. 3) emissions than diesel fuel. The benefits of biocomponents were more noticeable at 1500 rpm (Fig. 2a and Fig. 3a). The more favorable emissions were noticed for blends containing animal biocomponents compared to the plant origin ones (Figs. 2 and 3).

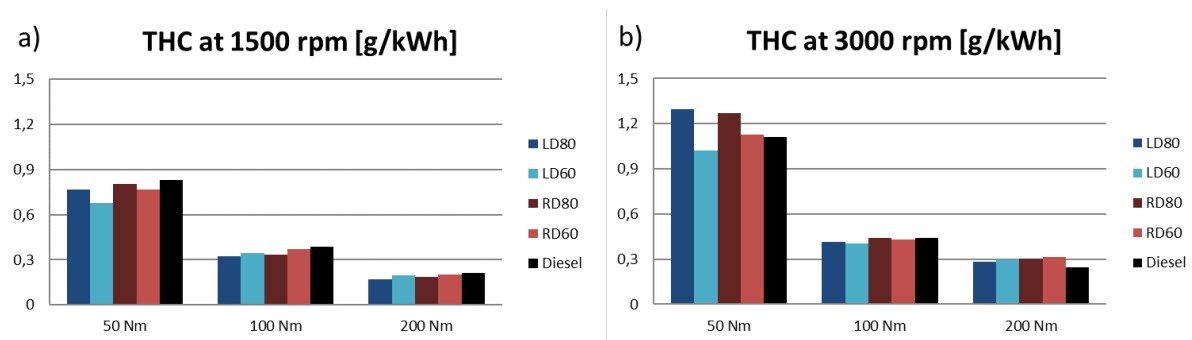


Fig. 2. Total hydrocarbon emission from an engine supplied with the analyzed fuel blends at rotational speeds of 1500 rpm a) and 3000 rpm b)

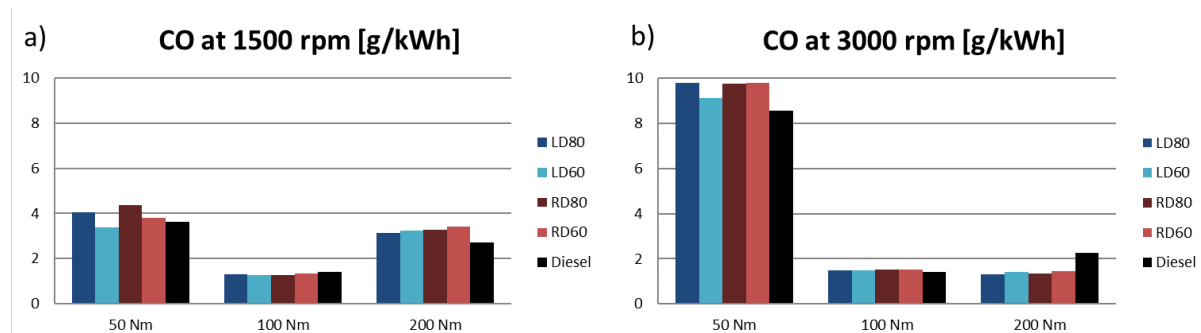


Fig. 3. Carbon monoxide emission from an engine supplied with the analyzed fuel blends at rotational speeds of 1500 rpm a) and 3000 rpm b)

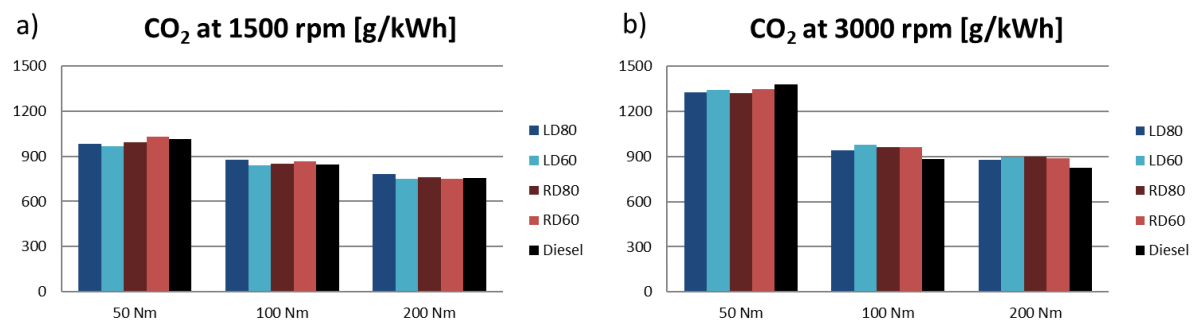


Fig. 4. Carbon dioxide emission from an engine supplied with the analyzed fuel blends at rotational speeds of 1500 rpm a) and 3000 rpm b)

Under the lowest load conditions, blends with a lower percentage of renewable components produced more satisfactory results than those with a higher percentage of biofuels. These results suggest that a high content of renewables in the blend may negatively affect THC and CO emissions in a low load operation. Therefore, improvement of the control algorithms of the injection system (injection timing

and pressure) is probably required to exploit the full potential of fuel blends containing high percentages of renewable components. The above hypothesis may also be confirmed by the fact that both mixtures containing higher percentages of biocomponents (LD80 and RD80) showed similar results. However, significant differences in the examined emission levels were clearly visible between blends containing lower quantities of biocomponents (LD60 and RD60) – Figs. 2 to 4.

Regardless of the engine rotational speed under the lowest load conditions, the examined blends were characterized by lower CO₂ emissions (Fig. 4) compared to the diesel fuel operation. However, beneficial CO₂ emission under these operating conditions caused higher emissions of THC and CO than diesel fuel (Figs. 2 and 3). At higher loads, CO₂ emissions were higher for all examined blends than for conventional diesel fuel (Fig. 4); this phenomenon can be attributed to significant differences in the specific consumption of the examined fuels (Tables 3 and 4).

In the vast majority of conducted experiments, LD60 was characterized by the lowest emissions of all examined exhausts relative to the remaining biodiesel blends. Engine efficiency was also satisfactory for experiments conducted using the LD60 blend (Tables 3 and 4). The reported results suggest that biocomponents derived from pork lard offer a viable alternative to those derived from rapeseed oil, especially when high percentages of biocomponents in the blend are considered.

5. CONCLUSIONS

This study evaluated the applicability of renewable components derived from animal fat and vegetable oil as fuel components for compression ignition engines. The fuel blends with a high content of biocomponents were evaluated in an engine designed for medium-duty vehicles. The results of the experiments performed on blends containing renewable components were compared with conventional diesel fuel, which was also a component of the analyzed blends. From the obtained results, the following conclusions can be drawn:

1. The use of renewable components as the dominant component of the blends does not reduce the engine's performance or lead to the occurrence of any undesirable phenomena during their combustion.
2. The use of fossil fuel alternatives is associated with higher brake-specific fuel consumption, determined by the type and percentage of biocomponents in the blend. The specific consumption of the tested fuel blends was correlated with the percentage and calorific value of the individual fuel components.
3. Biocomponents derived from pork induced a smaller decrease in engine performance compared to rapeseed-derived fuel components. These differences were exacerbated at higher rotational speed and under higher load conditions. In comparison with diesel fuel, greater differences in engine performance were noted for blends containing biocomponents derived from rapeseed oil than pork lard.
4. Application of the examined fuel blends induced significant differences in the exhaust emissions relative to diesel fuel. The following observations were made:
 - THC emissions decreased in all experiments conducted at the engine rotational speed of 1500 rpm.
 - CO₂ emissions increased in experiments conducted at the engine rotational speed of 3000 rpm and loads of 100 Nm and 200 Nm.
5. Irrespective of the type of biocomponent, to take full advantage of the blends containing a dominant percentage of renewables, optimization of the control algorithms of the injection system (especially if it was originally designed for a conventional diesel operation) may be required.

Despite the fact that in the vast majority of cases examined fuel blends are characterized by higher CO₂ emissions than diesel fuel, one should take into account that the combustion of biocomponents does not contribute to carbon emissions from anthropogenic sources. Moreover, on the basis of the information provided by “WELL-TO-TANK Report Version 4.a”, life-cycle analysis for different biofuels (produced from animal and plant origin feedstocks by different methods) shows 10 to 60 grams of CO₂ per 1MJ of energy in the final fuel, whereas the corresponding figure for conventional diesel

produced from fossil fuels is almost 50% higher (89 grams of CO₂ per 1MJ of energy in the final fuel) [40].

Notwithstanding the ongoing efforts to replace compression ignition engines with more environmentally friendly alternatives in passenger vehicles, for some time, these engines will continue to be the dominant power source for heavy- and medium-duty vehicles and machines, due to the lack of competitive options. Therefore, it is important to continue exploring the most environmentally friendly ways of using them.

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Received 03.08.2019; accepted in revised form 18.02.2021