Article citation info:
CZECHLOWSKI M, GOLIMOWSKI W, SĘK T, SZYMANOWICZ J. Exhaust opacity in a diesel engine powered with animal fats. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2015; 17 (1): 49–53.

Mirosław CZECHLOWSKI
Wojciech GOLIMOWSKI
Tadeusz SĘK
Jacek SZYMANOWICZ

EXHAUST OPACITY IN A DIESEL ENGINE POWERED WITH ANIMAL FATS

ZADYMIENIE SPALIN SILNIKA Z ZAPŁONEM SAMOCZYNNYM ZASILANEGO TŁUSZCZAMI ZWIERZĘCYMI*

The diversification of sources of energy has been recognised as one of the actions preventing the negative effects of human activity on the environment. In order to do so it is necessary to solve the problems related with the replacement of fossil fuels with biofuels, including the increase in the prices of food products caused by the dynamic development of biofuels made from plants. Therefore, the aim of the study was to make an experiment assessing the technical possibilities to replace diesel fuel with rendered animal fats. As results from the initial study, the kinematic viscosity of animal fats at a temperature of 120°C is comparable to that of diesel at 40°C. Apart from that, the diesel engine powered with animal fats emitted 70% less particulates in exhaust than the engine powered with a diesel fuel.

Keywords: *biofuels, pig fat, kinematic viscosity, exhaust opacity.*

Dywersyfikację źródeł energii uznano za jedno z działań zapobiegających negatywnemu oddziaływaniu człowieka na środowisko. W tym celu konieczne jest rozwiązanie problemów związanych z zastępowaniem paliw kopalnych biopaliwami, m. in. wzrost cen produktów spożywczych, wywołany dynamicznym rozwojem biopaliw pochodzenia roślinnego. Dlatego za cel badań przyjęto wykonanie eksperymentu, polegającego na ocenie możliwości technicznych zastąpienia oleju napędowego wytopionymi tłuszczami zwierzęcymi. Z przeprowadzonych badań wstępnych wynika, że tłuszcze w temperaturze 120°C charakteryzują się lepkością kinematyczną porównywalną do oleju napędowego w 40°C, ponadto zasilany nimi silnik ZS emitował o 70% mniej cząstek stałych w spalinach w porównaniu do silnika zasilanego olejem napędowym.

Słowa klucze: *biopaliwa, tłuszcz wieprzowy, lepkość kinematyczna, zadymienie spalin.*

1. Introduction

All over the world transportation is dependent on a continuous supply of liquid and gas fuels. Due to the increasing nuisance of vehicles emitting toxic gases to the natural environment many scientific institutions make attempts to solve the problem. One of such solutions is the introduction of fuels substituting fossil fuels, which are generally known as biofuels. They are made from different types of biomass by means of different technologies and they are processed into formed fuels.

Liquid fuels made from vegetable oils are a type of biofuels which stand the greatest chance for development in economy [13]. So far research results have proved that there are no technical barriers to the application of pure vegetable oil as a fuel for farming machinery [10, 22]. In 2006 Czechlowski et al. did not observe the negative influence of biofuels on the working parts of the injection pump in a farm tractor [7]. On the other hand, in 2001 Koniuszy noted that the penetration of biofuels into engine oil deteriorates the lubrication of the engine parts, which causes the need to change the oil in a diesel engine more frequently [16].

On the other hand, the use of biofuels made from vegetable oils is a serious social and economic problem. In 2012 Nonhebel stressed that the production of biofuels from biomass was a serious threat to food production [19]. In 2011 Mueller et al. published the results of research which prove that the prices of cereals were closely correlated with an increase in the supply of biofuels [18]. In 2013 Peri & Baldi proved a strong correlation of market prices between diesel and vegetable oil [21]. To sum up, we can say that an increase in the prices of diesel fuel strongly affects the prices of food and biomass, which biofuels are made from.

The replacement of diesel with biofuels made from plants is regarded as an environment-friendly action because the emission of CO_2 is reduced. As results from the study conducted by Dzieniszewski in 2009, as far as biofuels are concerned, the emission of CO_2 is much higher than from diesel if we consider the workload which is necessary to produce biofuels and the emission from their combustion in diesel engines [6]. This phenomenon is chiefly caused by considerable amount of work that goes into energy crops grown for specific purposes. In response to this information, in 2010 Pasyniuk stated that when diesel engines were powered with biofuels, the CO_2 balance was retained, because plants absorb the total amount of CO_2 emitted from engines powered with fuels made from plants [20]. It is also necessary to stress the fact that engines powered with biofuels emit much less toxic substances, i.e. carbon monoxide, hydrocarbons and particulates. In 2013 Shirneshan proved that these compounds were reduced by 30% when the share of biofuels reached 20% [24]. Also, in 2010 Kalam et al. found that as the share of biofuels in diesel increased, the emission of toxic compounds was considerably reduced [14]. However, in both cases the emission of nitrogen oxides increased. In 2010 Hossain & Davies proved that it was possible to reduce the emission of nitrogen oxides when diesel was partly replaced with sunflower oil

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl***

[12]. In 2005 Senthil et al. made experiments in which they powered an engine with hot animal fats and they observed that as the temperature of that fuel increased, the emission of nitrogen oxides was limited [25]. These results point to the fact that it is justified to produce biofuels from biomass which does not come directly from plant production. This will certainly enable the limitation or even abandonment of energy crops grown for a specific purpose.

The production of biofuels from non-food fats and animal fats is an interesting solution worth consideration. In 2012 Roszkowski found that 2015–2017 was the realistic time of implementation of the technologies enabling the production of biofuels from fats derived from the secondary market in the EU [23]. As results from the research conducted so far, there are no technical barriers which would make it impossible to power older generation engines with fats of different origin. In 2012 Czaczyk et al. made an active experiment in which they investigated the energetic parameters of the engine of a farm tractor powered with post-frying fats [5]. In 2013 Wegner et al. published the results of investigations of the energetic parameters of an engine powered with a fuel containing from 15% to 50% of used soybean oil [27]. In recent years there have also been numerous studies on the parameters of operation of a diesel engine powered with animal fat esters [2, 3]. In comparison with conventional fuels the application of biofuels contributes to reduction of exhaust opacity and increases the emission of NO_x [1]. On the other hand, the use of rendered animal fats or fats in the form of emulsion with ethanol as a fuel considerably reduces both exhaust opacity and the emission of NO_x [15, 26].

The amount of raw materials, i.e. animal fats and oils from the secondary market is limited. In 2010 Marczak published the estimates concerning the amount of animal fats produced in Poland which could be used for the production of biofuels without the negative effect on the prices of food products. He found that by 2020 every year Poland would have produced about 60 thousand Mg of cow and pig fat which was not used as food, including fats from slaughterhouse waste [17]. In 2003 Ferenc & Pikoń estimated the production potential of waste fats in Poland. They found that in 2002 Poland produced a total of about 130 thousand Mg of such fats and in the following year - about 150 thousand Mg. In the authors' opinion the data are strongly understated, because there was considerable discrepancy between the results of questionnaire surveys and the data from periodical reports on waste [7].

The analysis of the state of knowledge presented above was the basis for initial research which was conducted to determine temperature-induced changes in the rheological properties of rendered animal fats and the possibilities to reduce the exhaust opacity in a diesel engine in consequence of using fat heated to a temperature above 80°C as a fuel.

2. Research methodology

The research was conducted in two stages. In the first stage the distribution of the kinematic viscosity of pig fat in the temperature function was measured. In the second stage the exhaust opacity of a diesel engine powered with pig fat at different temperatures was measured.

The assumption was that the kinematic viscosity of pig fat would be measured within the range of temperatures from 60°C to 160°C at 10°C intervals. Simultaneously, the researchers agreed that each measurement would be made three times and the arithmetic mean of the three measurements would be assumed as the result.

Viscosity was measured according to the standard PN-77/C-04014. As a result of the measurement, the kinematic viscosity was determined. The measurement of fat viscosity consisted in measuring the flow time of 200 cm^3 of the fat under study at a particular temperature and the flow time of the same volume of distilled water at a temperature of 20°C under the conditions specified in the standard (PN-77/C-04014). Next, the relative viscosities were calculated in Engler degrees °E and on the basis of the results the kinematic viscosity of the fat under study was read from tables attached to the standard. Before the measurements the constant k was calculated for the Engler viscometer used in the investigations. For that purpose the flow time of distilled water was measured at a temperature of 20°C. The arithmetic mean of the three measurements was assumed as the constant k of the device.

During the measurements the viscometer was filled with hot pig fat at a higher temperature than the assumed measurement temperature. Simultaneously, the liquid which filled the water bath of the viscometer was preheated to the temperature at which the measurement was to be made. When the viscometer was filled with a sample, it was necessary to wait until the viscometer and the sample reached the assumed measurement temperature. When this happened, the flow time of the fat under study into a volumetric flask was measured.

In order to make an active experiment assessing the exhaust opacity was used a diesel engine with a displacement of 1588 cm^3 and nominal power of 37 kW at 4800 rpm. The fuel feed system consisted of a distributor injection pump with a system of indirect injection into the swirl chamber. Because of the fact that a comparative study was conducted, the degree of the engine wear was not taken into consideration in the control sample, where the investigations were made on standardised diesel fuel.

The engine was equipped with two fuel tanks – an unheated one for diesel and an insulated one, fitted with a heating system for animal fat. In order to reduce the heat loss the fuel hoses were fitted with an electric heating system, which enabled us to keep the set temperature of the fuel injected into the cylinders.

A Junkers H0 stationary hydraulic dynamometer was used to load the engine so it could reach thermal equilibrium. The dynamometer was directly connected to the engine flywheel by means of an articulated telescopic shaft.

In order to measure the exhaust opacity an optical opacimeter Radiotechnika DO 9500 was used. The basic technical specifications of the opacimeter are shown in the table below. The opacity was measured when the engine powered with the fuel under investigation was hot.

Table 1. Optical opacimeter Radiotechnika DO 9500 – technical specifications

Values measured	Range	Resolution	Unit
Exhaust opacity: Absorption coefficient k Opacity N	 0...∞ 0...100	 0.01 1 or 0.1	 m^{-1} %
Rotational speed	60...9999	1	rpm
Oil temperature T_{ol}	0...150	1	°C

The exhaust opacity was measured according to the following procedure. After the start-up the engine was initially warmed up and then it was loaded with its nominal power until it reached thermal equilibrium. Immediately after the warmup we determined the external operating characteristics of the engine powered with diesel. Then the exhaust opacity of the engine powered with a standard diesel fuel was measured.

The absorption coefficient k was measured with the free acceleration method, which consisted in loading the engine with the inertia of the rotating parts of the engine itself and the engine brake connected to it. In order to make the measurement the rotational speed of the engine was rapidly increased from the idle speed to the maximum speed by making a decisive move shifting the fuel dosage lever from the idle position to the position of the maximum fuel dose. In order to average the results the measurements were made ten times, with 15-second periods of the engine idling before consecutive measurements.

Having finished the measurement, the engine fuel system was filled with pig fat and for 15 minutes the engine ran at its nominal power in order to guarantee that the diesel was completely removed from the fuel system. Then the measurement procedure described above was repeated three times for selected temperatures of pig fat.

3. Discussing research results

The constant k for the viscosity measurement system was 50.66, where the coefficient of variation was <1%. The arithmetic means of the fat flow times, where the coefficient of variation was <5%, had the logarithmic distribution with the coefficient of determination $R^2>0.99$ until the moment of change in the temperature.

The kinematic viscosity of fat which was measured within the assumed temperature range (60–160°C) reached the values ranging from 1.8 to 12 $mm^2 \cdot s^{-1}$ and it was negatively correlated with the temperature $r=-0.94$ (Fig. 1).

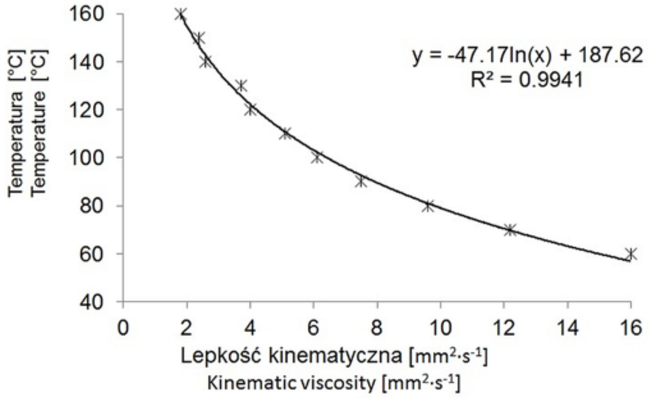

Fig. 1. The correlation between the kinematic viscosity of pig fat and heating temperature

The temperature where the kinematic viscosity of pig fat is similar to the kinematic viscosity of diesel at 40°C ranges from 120°C to 140°C. Animal fats contain about 35% of stearic acid and palmitic acid (melting point: 70°C and 64°C, respectively). Therefore, they retain the solid state of matter at ambient conditions [5]. The freezing point of such fuels can be changed chemically by the process of transesterification. As a result of the process, the freezing point of these fuels is about 10°C. According to Goodrum et al., animal fats can be used as a component of heating oil in heating installations, where the fuel is preheated and its storage conditions do not change [11].

The type of applied fuel and the temperature of pig fat did not have significant influence on the power generated by the engine. As results from the research, the engine powered with hot animal fat (fuel temperatures of 80°C, 120°C and 160°C) generated the average maximum power of 34.9 kW ± 4%, whereas the engine powered with diesel generated the power of 32.3 kW ± 8% (Fig. 2). Thus, as a result of a univariate analysis of variance with the 5% level of confidence, the type of applied fuel was not observed to have significant influence on the maximum power generated by the engine under investigation ($p= 0.08$).

The next stage of the research involved the measurement of exhaust opacity in the engine powered with diesel and then with rendered animal fats. The average value of exhaust opacity in the engine powered with diesel was $k=1.38\ m^{-1}$. When this value was compared with the values obtained when the engine was powered with hot animal fat, which ranged from $k=0.38\ m^{-1}$ (80°C) through $k=0.30\ m^{-1}$ (120°C) to $k=0.39\ m^{-1}$ (160°C), a considerable decrease in the exhaust opacity was observed, reaching about 70% (Fig. 3). Such a low value

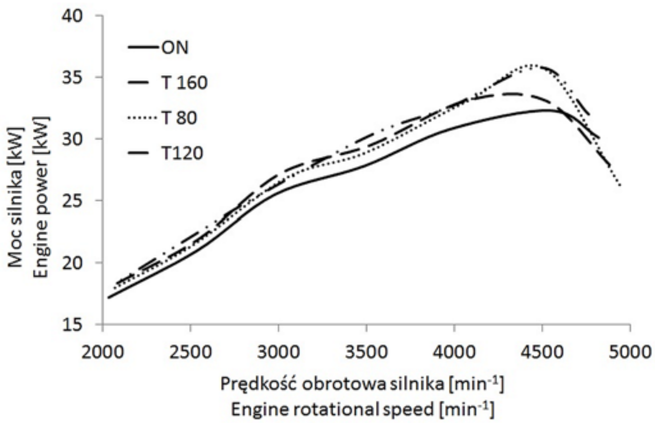

Fig. 2. The engine power at the maximum setting of the fuel injection pump; ON – diesel; T80, T120, T160 – pig fat at temperatures of 80°C, 120°C and 160°C, respectively

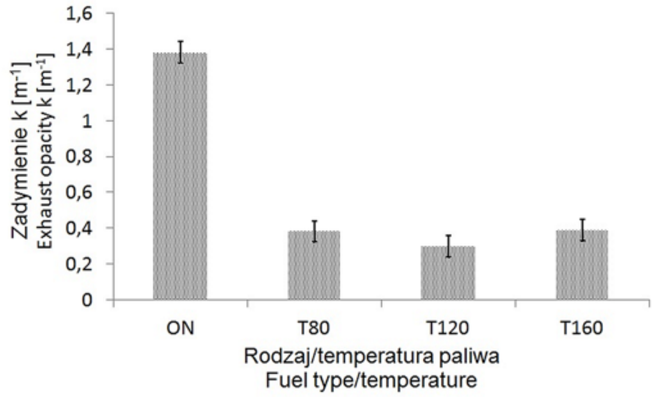

Fig. 3. A comparison of exhaust opacity in the engine powered with diesel and the engine powered with pig fat: ON – diesel; T80, T120, T160 – pig fat at temperatures of 80°C, 120°C and 160°C, respectively

of the exhaust opacity may have resulted from differences in the content of carbon and oxygen in the fuels under comparison. The content of carbon in diesel reaches 84-87% and there is almost no oxygen, whereas the content of carbon in animal fats is about 73% (m/m) and the content of oxygen is about 12.5% (m/m) [25].

4. Summary

As results from the literature, fats are a mixture of fatty acids, which are characterised by different flow temperatures, ranging from −14°C for linolenic acid to 70°C for stearic acid [8]. As results from the study by Golimowski et al., regardless of the type and origin the kinematic viscosity of fats is about 19.67 $mm^2 \cdot s^{-1} \pm 5\%$ at a temperature of 60°C (except post-frying fats) [9]. On the other hand, at lower temperatures the kinematic viscosity depends on the type of fat. Thus, in view of this fact and with reference to the findings of this research we can assume the hypothesis that the kinematic viscosity of fats made from plants will be similar to that of diesel at a temperature exceeding 120°C. In order to confirm the hypothesis it is necessary to conduct the research again according to the methodology developed by the authors.

In 2005 Senthil et al. proved that an increase in the temperature of animal fats used to power a diesel engine reduces the exhaust opacity. In comparison with the engine powered with diesel the opacity of exhaust emitted by the engine powered with fats at a temperature of 30°C was lower by about 30%. When the temperature increased to 70°C, the exhaust opacity was reduced by 60% in comparison with diesel [25]. The researchers observed that when the engine was powered with pig fat at a temperature of 80°C, the exhaust opacity was reduced by about 70% in comparison with the engine powered with diesel. Apart from that, further increase in the temperature of fat did not cause significant changes in the degree of exhaust opacity. Senthil et al. observed that the lower exhaust opacity resulted from the characteristics of heat release in the cylinders. During the first phase, when the pressure in the cylinders increased dynamically, the dynamics of heat release was lower when animal fats were applied. The situation was opposite at the second phase where the unburned fuel is completely burning [25]. This phenomenon was caused by the lower content of carbon in fat and by the presence of oxygen. The larger amount of heat at the second phase of fuel burning favours the higher temperature of exhaust emitted by the engine [2]. Barrios et al. observed that differences in the exhaust opacity of the engine powered with diesel and then with a mixture of biodiesel from animal fat and diesel (50/50) did not depend on the engine load. As the average velocity of the vehicle in motion increased, and in consequence, as the engine load increased, there were equal and directly proportional differences in the degree of exhaust opacity for all of the engine load values under investigation [3]. Another effective method of reduction of exhaust opacity is to use animal fat emulsified with ethanol [15]. Thus, it would be necessary to start research in order to make a complex assessment of the influence of fuels made from plants and animals at a temperature where the kinematic viscosity would be comparable to that of diesel at 40°C on the operation parameters and level of exhaust emission from a diesel engine.

5. Conclusions

- Rendered animal fats are characterised by the kinematic viscosity of 2.5–4 $mm^2 \cdot s^{-1}$ (diesel viscosity at 40°C) at temperatures ranging from 120°C do 140°C.
- Powering a diesel engine with hot animal fats considerably reduces exhaust opacity and increases the engine power by 10% in comparison with a diesel fuel. As results from the research, engines powered with hot animal fats at higher temperatures than 80°C emit 70% less solid pollutants into the atmosphere.
- The fuel can be preheated with the engine refrigerant and then heated to a minimum temperature of 80°C by means of the electric system. Further increase in the temperature of fats had no influence on changes in the engine parameters under investigation.

References

1. Armas O, Gracja-Contreras R, Ramos A. Emissions of light duty vehicle tested under urban and extraurban real-world driving conditions with diesel, animal fat biodiesel and GTL fuels. SAE Technical Paper 2013; 13240176.
2. Awad S, Loubar K, Tazerout M. Experimental investigation on the combustion, performance and pollutant emissions of biodiesel from animal fat residues on a direct injection diesel engine. Energy 2014; 69: 826-836.
3. Barrios CC, Dominguez-Saez A, Martin C, Alvarez P. Effects of animal fat based biodiesel on a TDI diesel engine performance, combustion characteristics and particle number and size distribution emissions. Fuel 2014; 117: 618-623.
4. Czechlowski M, Krysztofiak A, Adamski M, Antczak W. Wpływ stosowania oleju rzepakowego jako paliwa na trwałość aparatury wtryskowej silników ZS. Inżynieria Rolnicza 2006; 12(87): 85–92.
5. Czaczyk Z, Czechowski M, Golimowski W, Dereń B. Badanie parametrów fizycznych zużytych tłuszczów naturalnych i ich wpływ na parametry pracy silnika ciągnika rolniczego. Journal of Research and Applications in Agricultural Engineering 2012; 2(57): 51–57.
6. Dzieniszewski G. Wybrane aspekty ekologiczne i ekonomiczne zasilania silników Diesla paliwami roślinnymi. Inżynieria Rolnicza 2009; 6(115): 45–52.
7. Ferenc Z, Pikoń K. Przegląd rodzajów i ilości odpadów tłuszczowych i olejowych w Polsce. Archiwum Gospodarki Odpadami i Ochrony Środowiska 2005; 2: 69–80.
8. Gawęcki J. Prawda o tłuszczach. Warszawa. W: Instytut Danone FPZ 1997. ISBN 83-907366-1-6: 78.
9. Golimowski W, Golimowska R, Kliber A. Zależność temperaturowa lepkości kinematycznej tłuszczów zwierzęcych, olejów roślinnych oraz produktów reakcji transestryfikacji. Journal of Research and Applications in Agricultural Engineering 2011; 1(56): 50-55.
10. Golimowski W., Pasyniuk P., Berger A.W. 2013. Common rail diesel tractor engine performance running on pure plant oil. Fuel 2013; 103: 227–231.
11. Goodrum JW, Geller DP, Adams TT. Rheological characterization of animal fats and their mixtures with #2 fuel oil. Biomass and Bioenergy 2003; 3(24): 249–256.
12. Hossain AK, Davies PA, Plant oils as fuels for compression ignition engines: A technical review and life-cycle analysis. Renewable Energy 2010. 35: 1–13.
13. Jackowska I, Krasucki W, Piekarski W, Tys J, Zając G. Rzepak z pola do baku. PWRL Warszawa 2004, ISBN 83-09-01781-2: 134.
14. Kalam MA, Masjuki HH, Jayed MH, Liaquat AM. Emission and performance characteristics of an indirect ignition diesel engine fuelled with waste cooking oil. Energy 2011; 1(36): 397–402.
15. Kerihuel A, Santhil K.M, Belletter J, Tazerout M. Investigations on a CI Engine Using Animal Fat and Its Emulsions With Water and Methanol as Fuel. SEA Technical Paper 2005; 05011729.
16. Koniuszy A. 2001. Wpływ stosowania biopaliwa RME w silnikach wysokoprężnych pojazdów rolniczych na wybrane własności użytkowe oleju silnikowego. Inżynieria Rolnicza 2001; Nr 1(21): 135–140.
17. Marczak P. Wykorzystanie tłuszczu zwierzęcego jako biopaliwa – Wybrane zagadnienia. Opracowania tematyczne OT-589. Warszawa2010: 14.
18. Mueller SA, Anderson JA, Wallington TJ. Impact of biofuel production and other supply and demand factors on food price increases in 2008. Biomass and Bioenergy 2011; 5(35): 1623–1632.
19. Nonhebel S. Global food supply and the impacts of increased use of biofuels. Energy 2012; 1(37): 115–121.
20. Pasyniuk P. Ograniczenie emisji gazów cieplarnianych przez zastąpienie oleju napędowego olejami roślinnymi. Problemy Inżynierii Rolniczej 2010; 4: 79-89
21. Peri M, Baldi L. The effect of biofuel policies on feedstock market: Empirical evidence for rapeseed oil prices in EU. Resource and Energy Economics 2013; 1(35): 18–37.

22. Rathbauer J, Krammer K, Kriechbaum T, Prankl H, Breinesberger J. Rapsöl als Treib-stoffalternative für die Landwirtschaft BMLFUW-LE.1.3.2/0037-II/1/2006. Forschungsprojekt No. 1337: 317.
23. Roszkowski A. Biodiesel w UE i Polsce – obecne uwarunkowania i perspektywy. Problemy Inżynierii Rolniczej 2012. 3(77): 65–78.
24. Shirneshan A. HC, CO, CO2 and NOx emission evaluation of a diesel engine fueled with waste frying oil methyl ester. Procedia – Social and Behavioral Sciences 2012; 3(75): 292–297.
25. Senthil KM, Kerihuel A, Bellettre J, Tazerout M. Experimental investigations on the use of preheated animal fat as fuel in a compression ignition engine. Renewable Energy 2005; 9(30): 1443–1456.
26. Takayuki M, Takaaki M. Diesel Engine Operation and Exhaust Emissions When Fueled with Animal Fats. SEA Technical Paper 2005; 05013673.
27. Wegner EP, Lambert PD, Moyle TM, Koehle MA. Diesel vehicle performance on unaltered waste soybean oil blended with petroleum fuels. Fuel 2013; 107: 757-765.

Mirosław CZECHLOWSKI
The Institute of Biosystems Engineering
Poznań University of Life Sciences
ul. Wojska Polskiego 28, 60-637 Poznań, Poland

Wojciech GOLIMOWSKI
Department of Renewable Energy Sources
Institute of Technology and Life Sciences
ul. Biskupińska 67, 60-463 Poznań, Poland

Tadeusz SĘK
Jacek SZYMANOWICZ
The Institute of Biosystems Engineering
Poznań University of Life Sciences
ul. Wojska Polskiego 28, 60-637 Poznań, Poland

E-mails: mczech@up.poznan.pl , w.golimowski@itep.edu.pl