



EXHAUST EMISSIONS FROM THE ENGINE RUNNING ON MULTI-COMPONENT FUEL

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Abstract. Possible alternative raw materials for producing biodiesel fuel are as follows: *Camelina sativa* oil, fibre linseed oil and waste animal fat. The aim of this work was to analyse the emissions of the engine running on multi-component fuels containing fossil diesel fuel (D), linseed or *Camelina sativa* oil fatty acid methyl esters (LSME and CME respectively) and beef tallow (TME) fatty acid methyl esters. The concentration of fatty acid methyl esters (FAME) in the mixtures with fossil diesel fuel varied from 10% to 30%. The mass proportion of LSME (or CME) and TME in the mixtures was 1:4. The lowest NO_x concentration in exhaust gases was observed when the mixtures contained 10% of biofuel. For the mixtures containing CME and LSME, NO_x concentrations reached 290 and 295 ppm respectively when the engine rotation speed was 1200 min⁻¹ and 370 and 375 ppm respectively when rotation speed was 2000 min⁻¹. CO concentration was the lowest when fuel contained 30% of the FAME mixture. HC concentration was slightly higher when the mixtures containing LSME were used relative to the mixtures containing CME. The amount of HC did not fluctuate considerably (195÷254 ppm) at rotation speeds between 1200 and 2000 min⁻¹. Lower HC concentration was found in exhaust gas when the fuels containing 10% and 20% of biofuel were used. The lowest concentration of polycyclic aromatic hydrocarbons (PAHs) was found when the mixtures contained 30% of biofuel made of LSME or CME corresponding to 30 µg/m³ and 38 µg/m³ at a rotation speed of 1200 min⁻¹ and 640 µg/m³ and 670 µg/m³ at a rotation speed of 2000 min⁻¹ respectively. The greatest amount of smokiness at a high rotation speed of 2000 min⁻¹ was observed when the mixture contained 30% of multi-component biodiesel fuel. It was found that the fuel containing a mixture of 30% of LSME biofuel and 20% of CME biofuel had a small advantage.

Keywords: multi-component biodiesel fuel, biofuel, engine emissions, Bosch smoke index.

1. Introduction

The development of a method for biofuel production in Lithuania has been quite slow in past years. At present, interest in the production of biofuels (especially biodiesel fuel) has evidently been growing among the country's businessmen. In 2010, the production volume of biodiesel fuel increased to 89 thousand tons. The largest amount of biodiesel fuel in the EU countries is produced from rapeseed oil. Physicochemical parameters, engine and environmental characteristics of engines fuelled with such biodiesel fuel were widely investigated and compared with the above mentioned characteristics of fossil diesel fuel (Labeckas, Slavinskas 2006, 2009).

The further development of biofuel production is hindered by increased demand for the raw material of

biodiesel fuel – rapeseed – and by limited potential for its growth (290 thousand ha in Lithuania). This lack of resources has made searching for alternative raw materials for biofuel production essential.

Plants that are not adequate for food or forage are considered to be an alternative source of raw materials. These plants are usually used as raw materials for the generation of renewable energy, in paint, drug, textile and other industrial branches. Traditional plants could also be used for the abovementioned purposes.

False flax (*Camelina sativa*) as an example of such alternative sources of raw material is one of the oldest cultural plants. False flax belongs to the cruciferae family, along with rapeseed, mustard and cabbage (Vollmann *et al.* 2007). As false flax neither demands special soil nor climatic conditions, it is not difficult to grow. When

sown to the crops of leguminous plants as undersowing, false flax does not allow for the growth of plants lying on the soil surface for the whole vegetation period, even in the case of a large amount of precipitation. Additionally, false flax reduces the growth of weeds (Vollmann *et al.* 2007). The seeds of false flax contain 28÷42% of oil including a high content of unsaturated fatty acids. The first trials for growing false flax were conducted in Vežaičiai Branch of the Lithuanian Research Centre for Agriculture and Forestry. Studies on oil content in false flax seed showed that in case of spring type seed, it reached 40.3% while the oil content of winter type seed was lower and made 37%. These characteristics of false flax have garnered the interest of farmers.

Due to its strong contamination with pesticides, linseed oil produced from fibre flax seed is not suitable for producing edible oil. Under Lithuanian law, other usages are limited. Over the last five years, the average yield of flax seed has been 5.12 thousand tons per year. Thus, the analysis of the features of linseed oil and its possible use in the production of biofuels is meaningful. In addition, it has been found that the features of linseed oil from fibre flax do not differ from those of linseed oil from oil flax.

The processing rules for the waste of animal origin that is not used for food are presented in Regulation (EC) No 1774/2002 and Directive 2003/30/EC prepared with regard to the provisions of the group of the EU regulations and directives related to the usage, quality and hygiene of the waste of animal origin. This regulation indicates the categories of waste classification and principal procedures of accumulation, storage, processing, trade and export. Large amounts of animal (especially cattle) fats are produced in Lithuania, which, especially in waste, are not rationally used and pollute the environment. On average, twenty-six thousand tons of animal waste is formed every year. Because of the large availability of fatty wastes from meat, which is characterized by their low price, interest in the possibility of using fats of animal origin (beef tallow and pork lard) for producing fatty acid methyl esters (FAME) (Zheng, Hanna 1996; Hsu *et al.* 2001; Foglia *et al.* 1997) has recently arisen. The compositions of fatty acid methyl esters produced from false flax (CME) and linseed oil (LSME) do not differ greatly (Steinke *et al.* 2000; Makarevičienė *et al.* 2007). They cannot be used in their pure form because they do not satisfy the requirements of the Standard EN 14214:2003 regarding the iodine value, linolenic acid methyl ester content and oxidation stability.

Thus, it is meaningful to investigate the possibilities of improving the physical and chemical parameters of methyl esters. One of such possibilities is mixing fatty acid methyl esters of different origin (animal and vegetable) as well as the use of effective additives (depressants and antioxidants). The properties of multi-component fuel strongly influence the combustion process and pollutant formation. It is a key aspect of the present research on diesel engines and fuels (Raslavičius, Bazaras 2010a, 2010b, 2010c).

Therefore, it is essential to analyse the possibilities of using multi-component fuels composed of tallow and false flax (or linseed oil) fatty acid methyl esters and fossil diesel fuel (D) specifically for diesel engines. It is also important to determine engine emissions, as these new raw materials may affect them.

The aim of this research was to analyse the emissions from the engine running on multi-component fuel containing fossil diesel fuel, tallow fatty acid methyl esters and false flax (or linseed oil) fatty acid methyl esters, as well as to evaluate the dependence of harmful component content in engine emissions on the composition of the fuel.

2. Materials and Methods

2.1. Materials

The materials used for this research are as follows:

- fossil diesel fuel (D) that meets the requirements of Standard EN 590:2004;
- methanol (Aldrich Chemical Company, Inc);
- KOH (Aldrich Chemical Company, Inc);
- rapeseed oil fatty acid methyl esters (RME) that meet the requirements of Standard EN 14214:2003;
- linseed oil fatty acid methyl esters (LSME) that were produced when refined rapeseed oil was transesterified twice by the rectified methanol of 99.9% purity using an alkaline catalyst (KOH), transesterification yield was 98.1%;
- *Camelina sativa* oil fatty acid methyl ester (CME) was produced from *Camelina sativa* oil by applying the same alkali transesterification method as in the case of LSME, transesterification yield was 97.2%;
- tallow fatty acid methyl esters (TME) were produced from beef tallow by applying the same alkali transesterification method as in the case of LSME. Transesterification yield was 97.8%.

The following multi-component fuel mixtures were used for the analysis of engine emissions (percentage expressed by volume):

- 100% RME;
- 100% D;
- B10 – 90% D, 2% LSME, 8% TME;
- B20 – 80% D, 4% LSME, 16% TME;
- B30 – 70% D, 6% LSME, 24% TME;
- B10* – 90% D, 2% CME, 8% TME;
- B20* – 80% D, 4% CME, 16% TME;
- B30* – 70% D, 6% CME, 24% TME.

2.2. Methods

Short-term engine tests were conducted using a single cylinder direct injection engine, of the type AVL 502.019 that was placed on the test stand. The following test conditions were chosen:

- rotation speed – 2000 min⁻¹, torque – 42.42 Nm;
- rotation speed – 1200 min⁻¹, torque – 9.7 Nm.

Torque was measured using a dynamometer (HBM U1) and rotation speed was measured applying an impulse meter (Vibro-Meter JP 1412). NO_x, HC, CO and CO₂ emissions in exhaust gases were determined using

an AMA exhaust gas analyser (Pierburg Instruments).

Measurement limits for HC – 0÷1000 ppm, NO – 0÷1000 ppm, CO₂ – 0÷20 % and CO – 0÷2500 ppm. Measurement accuracy is ±5%.

NO_x and CO concentrations in exhaust gas were measured using an AMA analyser (Pierburg Instruments) fitted with a chemiluminescence detector (CLD 4000) and an infrared detector respectively; HC was measured using a flame ionization detector (FID 4000). The Bosch smoke index was measured using a Bosch smoke meter (Pierburg PR 1).

PAH analysis was carried out employing two different methods: 1) laser induced fluorescence spectrometry (LIF, Optimare) and 2) liquid chromatography (HPLC, Varian, diode detector). The average values of PAH concentration determined by applying the above mentioned methods were calculated.

PAH samples were collected on Pall membrane filters (T60A20). The loaded filters were heated at a temperature of 300°C for 8 hours and kept in a dessicator before analysis. The PAH samples used for spectrometry were prepared by extraction from the filters (toluene; 25 min) using an ultrasonic bath. PAH content was measured at a wavelength of 355 nm. The samples used for liquid chromatography were prepared by applying PAH extraction with toluene for 90 min. Excess toluene was removed using a Rotovac rotary separator (by rotary evaporation). Polar compounds were extracted from the solution applying conventional column chromatography (Sorbent Strata S1-1 from Phenomenex). Finally, the PAH phase was extracted using a mixture of cyclohexane and dichloromethane (9:1).

For the most part, all analyses were performed in triplicate. The values of the experiments were evaluated using *Microsoft Excel* software calculating the mean value of parallel measurements.

3. Results and Discussions

The analysis of the quality of *Camelina sativa* oil (CME) and linseed oil methyl esters (LSME) demonstrated that such methyl esters did not meet the requirements of Lithuanian Standard LST EN 14214:2003 for the quality indicators of biodiesel fuel. These fuels have too high iodine value which is 164.9 g I₂/100 g for CME and 176.2 g I₂/100 g for LSME (standard specifies a maximum of 120 g I₂/100 g). CME and LSME esters also have too high content of unsaturated fatty acids. Linolenic acid methyl esters content in CME and LSME is 44.8% and 48.0% accordingly, whereas the maximum limit under standard is 12%. For these reasons, pure esters of vegetable origin could not be used as fuel for diesel engines. On the contrary, beef tallow has low unsaturated fatty acid content, and therefore the iodine value of beef tallow methyl esters (TME) is low – 51.5 g I₂/100 g; thus, they do not contain linoleic acid methyl esters at all. The assumption was made that when mixing CME or LSME with TME in the appropriate ratio, biofuel meeting the requirements of Lithuanian Standard LST EN 14214:2003 can be obtained. The performed tests have disclosed that the quality parameters of the mixtures containing LSME or CME and TME in mass proportion 1:4 meet the requirements of Lithuanian Standard LST EN 14214:2003 (Table 1).

Table 1. Quality indicators for the mixtures containing CME or LSME and TME in mass proportion 1:4

Parameter	Unit	Requirements of Lithuanian Standard LST EN 14214:2003		LSME + TME (1:4)	CME + TME (1:4)
		min	max		
Ester content	% (mass)	96.50	–	97.80	97.70
Density at 15°C	kg/m ³	860	900	862	864
Viscosity at 40°C	mm ² /s	3.50	5.00	4.70	4.70
Flash point	°C	120	–	125	128
Sulfur content	mg/kg	–	10	9	9
Conradson carbon residue	% (mass)	–	0.30	0.20	0.25
Cetan number		51	–	52	52
Water content	mg/kg	–	500	480	450
Total impurities	mg/kg	–	24	17	19
Oxidation stability at 110°C	h	6.00	–	6.40	6.50
Acid value	mg KOH/g	–	0.50	0.48	0.45
Iodine value	g I ₂ /100 g	–	120	77	74
Linoleic acid methyl ester content	%	–	12	9.60	8.90
FAME composition:					
saturated	%	–	–	28.30	29.40
unsaturated	%	–	–	71.70	70.60
Methanol content	% (mass)	–	0.20	0.18	0.17
Free glycerol	% (mass)	–	0.02	0.02	0.02
Total glycerol		–	0.25	0.20	0.25

Based on the existing usage of diesel fuels containing up to 30% of biodiesel fuel in some EU countries, the environmental characteristics of multi-component fuel containing from 10% to 30% of fatty acid methyl esters in the mixtures with fossil diesel fuel were analyzed. More details about the composition of tested fuels are presented in Chapter 2.1. The elemental composition and calorific value of tested multi-component fuel as well as of pure materials used for preparing mixtures are presented in Table 2.

Table 2. The elemental composition of fuel

Fuel	C %	H %	O %	Hu, MJ/kg
Fossil diesel fuel	87.0	13.0	0.0	38.6
RME	77.0	12.3	10.7	38.1
CME	75.6	12.7	11.7	38.5
LSME	76.7	12.0	11.3	38.3
TME	76.7	12.1	11.2	38.4
B10 (90% D, 2% LSME, 8% TME)	85.9	12.9	1.2	38.6
B20 (80% D, 4% LSME, 16% TME)	84.9	12.8	2.3	38.6
B30 (70% D, 6% LSME, 24% TME)	83.9	12.7	3.4	38.5
B10* (90% D, 2% CME, 8% TME)	85.9	12.9	1.2	38.6
B20* (80% D, 4% CME, 16% TME)	84.8	12.8	2.4	38.6
B30* (70% D, 6% CME, 24% TME)	83.8	12.8	3.4	38.5

A comparison of the elemental composition show that oxygen content increases along with a growth of fatty acid methylesters in fuel mixtures. Pure fatty acid methyl esters contain 10.7÷11.7% of oxygen differently from fossil diesel fuel not containing oxygen.

The calorific value of all tested fuels decreases with an increase in the content of fatty acid methyl esters in fuel mixtures. Pure fossil diesel fuel is characterized by the highest calorific value that equals 38.6 MJ/kg. Linseed oil methyl esters are characterized by the lowest calorific value that is equal to 38.3 MJ/kg.

In order to evaluate the influence of the new kinds of multi-component fuels on the environment (consid-

ering the concentration of harmful components), the emissions of the analysed engine were taken from fuels composed of fossil diesel (D), tallow (TME) and linseed (LSME) or false flax (CME) fatty acid methyl esters. A comparative analysis of the concentrations of harmful components in the emissions from the engine was performed when the engine was fuelled with six mixtures containing linseed and false flax oil fatty acid methyl esters.

The concentration of fatty acid methyl esters in the mixtures with fossil diesel fuel varied from 10% to 30%. Physicochemical parameters of the tested fuel are presented in Table 3. For comparison, the concentrations of harmful components in the exhaust gases of the engine fuelled with pure RME and D were measured.

According to the results of the performed analyses, when different types of fuels are used, the engine torque and power, in principal, do not change. Under certain engine conditions, i.e. at a rotation speed of 1200 min⁻¹, torque of 9.7 Nm and power of 1.22 kW, the temperature of exhaust gas changed from 159.3 to 171.5°C with an increase in the amount of animal fatty acid methyl esters in fuel mixtures from 8% to 24%. When rotation speed was increased up to 2000 min⁻¹ with the torque of 42.4 Nm and the power of 8.88 kW, the temperature of exhaust gas changed from 526.8 to 563.5°C. The temperature of exhaust gas was slightly higher when multi-component fuels were used, for example, pure RME and D. When the engine was working with pure RME and D at a rotation speed of 1200 min⁻¹, the temperature of exhaust gas was 159.3°C. When rotation speed was increased up to 2000 min⁻¹, the temperature of exhaust gas increased to 526.9°C in the case of fossil diesel fuel and to 532.9°C in the case of RME.

Nitrogen oxides (NO_x), the concentrations of which are evaluated in the engine tests, cover a number of compounds, including nitrogen monoxide (NO), nitrogen suboxide (N₂O) and nitrogen dioxide (NO₂). They are formed within the combustion process at high temperatures and found in the exhaust gases of transport means and industry as a result of burning fuel oil and coal. The effect of nitrogen oxides on greenhouse gas effect is considerable. Data presented in Fig. 1 show that the amount of nitrogen oxides is larger when the engine is working at a higher rotation speed. It was noted that the largest amounts of NO_x were emitted

Table 3. Physicochemical characteristics of multicomponent fuels and limit values of standards

Parameter	EN 14214:2003	EN 590:2004	RME	D	B10	B20	B30	B10*	B20*	B30*
Ester content % (m/m)	min 96.50	max 5	98.3	–	10	20	30	10	20	30
Cetane number	min 51		55	51	51	52	52	51	52	52
Density at 15°C	860÷900	820÷845	880	830	835	842	851	832	840	853
Viscosity at 40°C	3.50÷5	2÷4.50	4.30	3.60	3.70	3.85	3.90	3.70	3.80	3.90
Ash content % (m)	max 0.02		0.02	0.01	0.01	0.01	0.02	0.01	0.01	0.01
Copper strip corrosion (3 hours at 5°C)	1		1	1	1	1	1	1	1	1
CFPP	C class (min -5°C)		-9	-8	-7	-6	-5	-7	-6	-5

when pure RME was used. Compared with emissions from pure D, an increase in NO_x emissions by 12 ppm at a rotation speed of 1200 min⁻¹ and by 77 ppm at a rotation speed of 2000 min⁻¹ was determined when the engine was fuelled with pure RME.

This behaviour can be explained by the fact that an increased amount of oxygen in fuels leads to higher combustion temperatures, and therefore to a larger number of nitrogen oxides in the emissions. The largest amount of oxygen is found in pure RME. The NO_x emissions obtained when the engine was fuelled with fuel mixtures containing similar amounts of CME or LSME were also similar. The smallest NO_x concentrations in exhaust gases were determined when B10 and B10* were used. Accordingly, these concentrations reached 290 and 295 ppm respectively under a rotation speed of 1200 min⁻¹ and 370 and 375 ppm respectively under the speed of 2000 min⁻¹.

Carbon monoxide is formed during the combustion process, specifically in cases where incomplete burning and a lack of oxygen in the environment can be noticed. CO concentrations in car exhaust gas are limited to 4% of the volume in accordance with Lithuanian normative documents.

The results of the analyses of carbon monoxide concentrations in exhaust gases using multi-component mixtures are presented in Fig. 2. The highest concentration of CO was observed when the engine was fuelled with pure fossil diesel fuel. When multi-component fuel and RME were used, the concentration of carbon monoxide at a rotation speed of 1200 min⁻¹ was almost in-

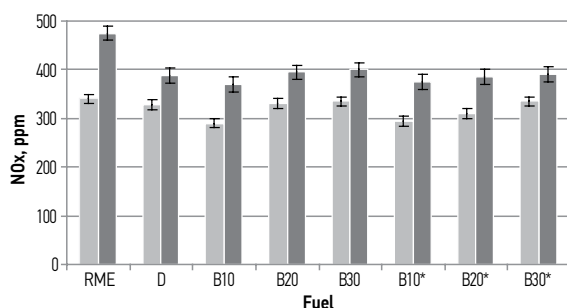


Fig. 1. The dependence of NO_x emissions on fuel composition at the engine rotation speed of:
 ■ - 1200 min⁻¹ ■ - 2000 min⁻¹

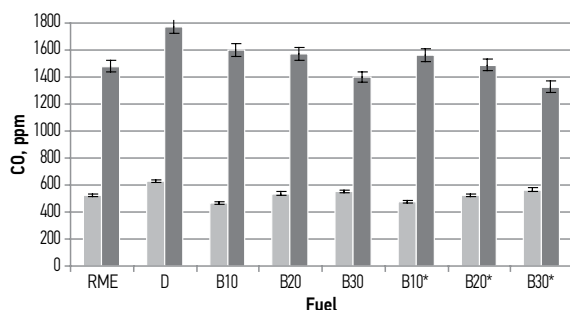


Fig. 2. The dependence of CO emissions on fuel composition at the engine rotation speeds of:
 ■ - 1200 min⁻¹ ■ - 2000 min⁻¹

dependent of the composition of fuels and other factors; concentration changed in narrow limits from 475 ppm (mixture B10*) to 565 ppm (mixture B30*). In the case of a higher engine rotation speed of 2000 min⁻¹ and multi-component fuel containing 10 and 20% fatty acid methyl esters, CO concentration was higher in comparison to that obtained when the engine was fuelled with pure RME. Overall, we have found that CO concentration decreases when the amount of biodiesel fuel in multi-component fuels increases, and it is the smallest when the fuels B30* are used.

Another index that allows for the evaluation of fuel influence on the human organism and the environment is the concentration of carbon monoxide in exhaust gases. Carbon monoxide (CO) is an odorless, tasteless and colorless gas that does not irritate mucous membranes. However, it is especially hazardous as the person does not feel the presence of this gas in the environment. When carbon monoxide enters lungs, it finds its way to the blood through air cells. Once in the blood, carbon monoxide joins haemoglobin and forms carboxyhemoglobin, which is much more stable (approximately 200 times more) than oxyhemoglobin. When B30 and B30* are used CO concentrations reached 550 ppm and 565 ppm under rotation speeds of 1200 min⁻¹ and 1400 ppm respectively and 1327 ppm under a rotation speed of 2000 min⁻¹.

Hydrocarbons (HC) are formed in exhaust gases when incomplete burning of fuels is noticed. These emissions may have not only toxic (alkanes or alkenes) but also cancerogenous (e.g. polycyclic aromatic hydrocarbons) effects (Munack *et al.* 2003). Polycyclic aromatic hydrocarbons (PAHs) are formed when acetylene polymerizes. PAHs find their way from the air to water, soil and vegetative food products.

Fig. 3 presents the measurement results of hydrocarbon (HC) concentration in exhaust gases when the engine was set at rotation speeds of 1200 min⁻¹ and 2000 min⁻¹. The obtained results show that in cases of using multi-component fuel, CH concentration in the emissions from the engine decreases in comparison with concentration when pure RME is used. The lowest concentration of HC in exhaust gases was observed when pure fossil diesel fuel was used. HC concentration increased with an increase in the amount of multi-

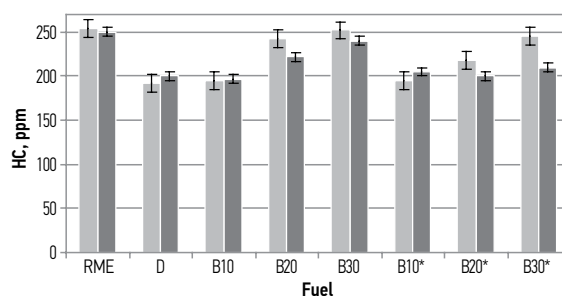


Fig. 3. The dependence of HC emissions on fuel composition at the engine rotation speeds of:
 ■ - 1200 min⁻¹ ■ - 2000 min⁻¹

component fuel in the mixtures with fossil diesel fuel. It was noticed that when the mixtures containing LSME were used, HC concentration was slightly higher in comparison to the mixtures containing CME. The amount of HCs did not fluctuate considerably (195–254 ppm) at rotation speeds in the range from 1200 to 2000 min^{-1} and differed among themselves by about 20%. More generally, it can be stated that lower CH concentration in exhaust gases is found when fuels B10 (195 ppm and 197 ppm at rotation speeds of 1200 min^{-1} and 2000 min^{-1} respectively), B10* (195 ppm and 205 ppm) and B20* (218 ppm and 200 ppm) were used.

The analysis of PAHs determined that their changing tendencies differed up to 20 times for different rotation speeds (Fig. 4). The largest PAH amounts corresponding to 820 $\mu\text{g}/\text{m}^3$ and 65 $\mu\text{g}/\text{m}^3$ at the rotation speeds of 2000 and 1200 min^{-1} respectively were found when pure fossil diesel fuel was used. Accordingly, when the amount of fatty acid methyl esters in the mixture increased, PAH amounts in exhaust gases decreased. The lowest PAH concentration was found when B30 and B30* were used: 30 $\mu\text{g}/\text{m}^3$ and 38 $\mu\text{g}/\text{m}^3$ respectively at a rotation speed of 1200 min^{-1} and 640 $\mu\text{g}/\text{m}^3$ and 670 $\mu\text{g}/\text{m}^3$ respectively at a rotation speed of 2000 min^{-1} . It can be expected that PAH would reach minimum between B30 and B40, however, this will require additional analyses.

One of the most important and, at the same time, regulating indexes considering the evaluation of fuel effects on the environment and human organism is the evaluation of the content of solid particles emitted from the exhaust gases of the engine. The largest amount of solid particles (soot) is found in the emissions from diesel engines. They are composed of various organic and inorganic compounds. The largest part of organic compounds is soot (carbon compounds) and not burnt or partly burnt substances and oils, as is commonly thought. Inorganic compounds are sulfates, water and metal compounds. The percent composition of solid particles depends on various parameters: the character of burning, working conditions of the engine (rotation speed and torque), the quality of fuels and oils and the degree of wear-and-tear of the engine (Wachter, Cartellieri 1987). Soot is formed when fuels find their way into the environment at a high temperature that contains a small amount of oxygen. The reactions that result in the formation of soot have not been completely explained. Solid particles are of various sizes, and therefore the ef-

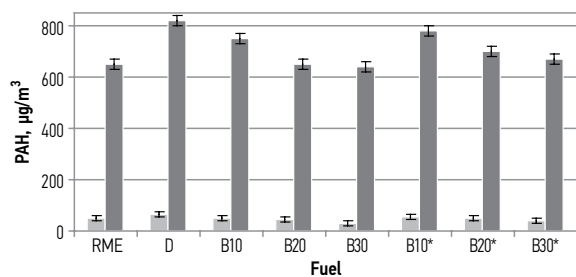


Fig. 4. The dependence of PAH emissions on fuel composition at the engine rotation speeds of:
 ■ – 1200 min^{-1} ■ – 2000 min^{-1}

fect on the human organism depends on how large the particle is. Wichmann (2002) analysed the stages of the solid particles of diesel engines; the stages of the particles were classified as small particles ($<2.5 \mu\text{m}$) and, more commonly, ultra small ($<0.1 \mu\text{m}$) ones. Both stages have a toxic effect on the human organism. Specifically, emissions from diesel engines increase the risk of cancer. PAHs are absorbed on the surface of the solid particles of soot, and therefore increase carcinogenicity. These small particles find their way into lungs, along with air, through airways. An interesting point is that very small particles are even more toxic than small particles, especially in older populations (Heinrich 1998).

Various methods are used for evaluating the concentration of solid particles. Usually, the determination of smokiness according to the Bosch scale is used. In individual cases, the method for determining the amount of solid particles is employed. When an environmental effect of the prepared fuels was analysed, both methods were applied to determine the amount of solid particles. Fig. 5 presents the results on determining smokiness according to the Bosch scale.

Data on smokiness analysis (Fig. 5) show that at a low rotation speed of 1200 min^{-1} , smokiness values are very small (from 0 to 0.07 Bosch smoke index) and change slightly with fuel composition. At this rotation speed, pure D was characterised by having the largest amount of smokiness at 0.08 Bosch smoke index. The lowest value of smokiness was observed when the engine was fuelled with B30 (0.01 Bosch smoke index). When the rotation speed of the engine was increased up to 2000 min^{-1} , a significant increase in smokiness was noticed. When the engine was fuelled with pure fossil diesel fuel, smokiness value was the highest and reached 4.8 Bosch smoke index. Depending on the sort of the used multi-component fuel, the amount of smokiness varied from 3.8 to 4.75 Bosch smoke index.

On the contrary to the behaviour observed at small rotation speeds, smokiness observed when the engine was fuelled with multi-component fuel exceeded smokiness in the case of pure RME. When the concentration of multi-component fuel containing LSME was increased in the mixture with fossil diesel fuel, the values of smokiness decreased proportionally from 4.6 to 4.05 Bosch smoke index. Alternatively, when fuel with CME was used, the largest amount of smokiness was observed

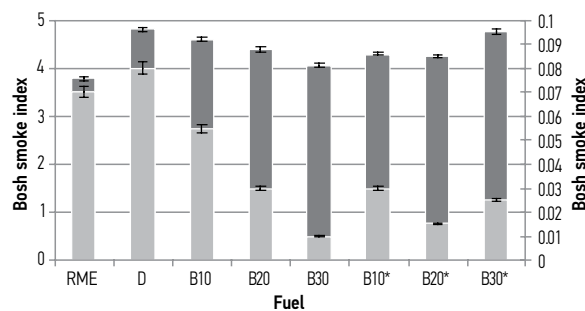


Fig. 5. The dependence of the Bosch smoke index on fuel composition at the engine rotation speeds of:
 ■ – 1200 min^{-1} ■ – 2000 min^{-1}

when the mixture contained 30% of multi-component biodiesel fuel. More generally, it can be stated that on the basis of the measurement units of smokiness, B30 and B20* multi-component fuels had a small advantage.

4. Conclusions

- The lowest NO_x and HC concentrations in exhaust gases were detected when multi-component fuel mixtures contained 10% of fatty acid methyl esters.
- The lowest concentration of CO and smokiness was observed when fossil diesel fuel was mixed with 30% of fatty acid methyl esters (a mixture of 20% of *Camelina sativa* oil or linseed oil fatty acid methyl esters and 80% of tallow fatty acid methyl esters).
- The analysis of polycyclic aromatic hydrocarbons determined that their changing tendencies differed by 20 times at different rotation speeds. When the amount of fatty acid methyl esters in the mixture increased, the amounts of PAH decreased.
- The smallest amount of PAH was found when the fuel mixture contained 30% of the mixture of fatty acid methyl esters (20% of *Camelina sativa* oil fatty acid methyl esters and 80% of tallow fatty acid methyl esters).
- A comparison of the emissions from the engine running on multi-component fuels composed from D-LSME-TME and D-CME-TME points that concentrations of harmful components in exhaust gases were almost the same.

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