EFFECTS OF FOSSIL DIESEL AND BIODIESEL BLENDS ON THE PERFORMANCES AND EMISSIONS OF AGRICULTURAL TRACTOR ENGINES

by

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Original scientific paper
DOI: 10.2298/TSCI111122106T

Rapid growth in the energy consumption has conditioned the need for discovering the alternative energy resources which would be adapted to the existing engine constructions and which would satisfy the additional criteria related to the renewability, ecology, and reliability of use. Introduction of biodiesel has been the focus of attention over the last ten years. The aim of this research is to investigate the influence of biodiesel on the performances and exhaust gas emissions of medium power agricultural tractor engines (37-66 kW). The reason for the selection of this category is that those types of tractors are most frequently used in agriculture.

In this research biodiesel produced from sunflower oil was blended with fossil diesel. Biodiesel, fossil diesel, and fossil diesel blends with 15, 25, 50, and 75%v/v biodiesel were tested for their influence on the engine performances and emissions. The testing was performed on a four-cylinder diesel engine with 48 kW rated power. The experimental research on the engine performances was conducted in compliance with OECD test CODE 2, and the exhaust gas emissions were tested according to the ISO 8178-4, C1.

The use of biodiesel and fossil diesel blends reduced the engine power with the increase of biodiesel share in the blend. However, the exception was the blend with 15%v/v biodiesel which induced a slight increase in the engine power. Depending on the share of biodiesel in the blend all blends fuels showed increased specific fuel consumption compared to the fossil diesel. Thermal efficiency increased as a result of more complete combustion of biodiesel and fossil diesel blends. The exhaust gas emissions implied that the addition of biodiesel reduced the content of CO_2 and CO, as well as the temperature of exhaust gases, but it increased the emission of NO_x.

Key words: *biodiesel, diesel, tractor, performance, emissions*

Introduction

Energy consumption is constantly increasing all over the world in spite of the rationalization measures that have been undertaken. Energy used in the traffic has increased by 16.42% over the last ten years reaching the level of 1.675.035 kt of oil equivalent [1]. Liquid fossil fuels are the main and most frequently used fuels for mobile machinery. This refers not only to the basic means of transportation, but also to a wide range of machinery used in the construction business, industry, agriculture. Considering the fact that the entire development of mobile machinery is based on the use of liquid fossil fuel, it is completely unrealistic to expect a shift from this

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trend to a mass development and use of new engine constructions that would be suitable for some other type of fuel. Therefore, the studies have been focused on discovering the fuel that would be adaptable to the existing engine constructions and that would meet the criteria regarding renewability, ecology and reliability of use. Fulfillment of the mentioned criteria is the basis for a successful fossil fuel replacement by some other types of fuel.

During the last decade biodiesel has become the most common renewable liquid fuel due to its possibility to meet the set requirements of the previously mentioned criteria. Namely, the use of biodiesel does not require any type of engine modifications or modifications of the fuel injection system. The exceptions are older engine constructions which need a replacement of sealant and fuel injection hose [2]. In its composition biodiesel is a fatty acid methyl ester. It is produced from vegetable oils or animal fats [3] which give biodiesel the renewability feature. The third ecology-related criterion gives biodiesel the greatest advantage over fossil diesel. It is well known that fossil diesel consists of hundreds of different carbohydrate chains with sulfur residue and remaining crude oil. Also, even the low sulfur and low aromatic fossil diesel fuels contain 20-24% of aromatics (benzene, toluene, xylene, *etc*.) which are volatile, toxic, and cancerogenic [4]. On the other hand, biodiesel does not contain sulfur or aromatic compounds. It reduces the possibility of engine wear because biodiesel is characterized by good lubricating properties when compared to fossil diesel and low sulfur diesel fuels [5]. This is how the fourth criterion is met (the reliability of use).

Based on the experience from biodiesel use, the performances of engine (power, torque, and fuel consumption) using biodiesel are similar to the engine performances provided by fossil diesel combustion [6].

The emissions of HC, CO [7], and particulate matter (PM) are reduced with biodiesel use. The CO emission is lowered by 30-50%, depending on the share of biodiesel in the blend. This is mainly due to the higher content of oxygen and lower hydrogen and carbon content [8]. Some authors have discovered that the emission of CO_2 occurs in the combustion process of biodiesel within the limits from 20% to 25% of total fossil diesel combustion [9]. As opposed to them, other authors provide the results according to which there is no significant difference in the CO_2 emission [10].

Nevertheless, besides the stated advantages, the use of biodiesel poses some problems as well. According to the previous studies, the use of biodiesel increases the content of NO_x in the combustion products [7, 11]. Higher NO_x content in the combustion products can be explained by high oxygen content in biodiesel [12]. Since the reduced NO_x content represents an important parameter in the introduction of EURO 3 and 4 norms on the exhaust gas emissions, application of devices for further exhaust gas treatment is necessary [11, 13]. Unfavorable low temperature characteristics of biodiesel raise the problems of engine start and use of diesel engines in cold weather [14]. Another disadvantage of biodiesel use lies in high hygroscopy because biodiesel absorbs water during storage [15].

Oxidation stability is one of the biggest problems related to the use of biodiesel. The Rancimat test (ISO 6886), adopted within the standard EN 14214 for oxidation stability, regulates the minimal induction period of 6 hours [16]. Still, meeting such a limit is difficult in practice unless antioxidants are added. According to the conducted researches the strong tendency towards the oxidation is a consequence of multiple double bonds present in one chain of fatty acids [17] which is why the use of oil with high content of linoleic and linolenic acid could represent the problem for biodiesel use.

Another problem related to the biodiesel use is its price conditioned primarily by the price of the raw material [18]. Biodiesel is produced from different plants (soybean, sunflower, oil seed rape, palm, algae) and raw material obtained from animals (animal fat), but it can also be produced from waste oil and grease. The use of agricultural crops (sunflower, soybean, oil seed rape) is especially important for farmers because these crops are in the sowing structure so the farmers are familiar with the technology of their production. Apart from that, by-products (oil cake) can be used as animal feed, which reduces the biodiesel price by about 20-25%. Also, valorization of glycerol can reduce the biodiesel price by 2.1%. Furthermore, with appropriate choice of catalyzator (KOH) and acids for neutralization, salts from biodiesel neutralization can be qualitatively valorized as a product for agriculture. This primarily refers to the production of high quality potassium foliar manures (fertilizers) for crops. One ton of biodiesel gives about 15-20 kg potassium sulphate (K_2SO_4) [19]. Another by-product in the oilseed rape production is 4.4 t/ha of plant mass with calorific value of 17.400 kJ/kg [20]. From the economic aspect, valorization of the above mentioned by-products can make biodesel price competitive with respect to fossil diesel fuel. Previous research indicates that biodiesel production is multidisciplinary problem and that it is not only important for energetics and ecology [21]. One of the more important aspects of introduction of biodiesel is the increase in the employment rate. Namely, according to the "National Biodiesel Board" report it is expected that in 2012 biodiesel production will provide jobs for 78.000 people in the USA, and that 100 million of biodiesel liters will increase the gross domestic product by about 386 billion [22]. The importance of biodiesel is also evident in rural development. Careful planning of production capacities would actuate rural development and decrease the migration of people into cities.

Over the past few years numerous studies have published the results of comparative engine tests for fossil diesel, biodiesel and their blends. Interestingly, almost all the tests have been performed for either low power engines with the power of up to 5 kW, or the high power engines that have more than 100 kW power. On the other hand, only a few tests have been performed for medium power engines (37-66 kW) which are most commonly used in agriculture by tractors that perform numerous agrotechnical operations. Out of a total number of two-axle tractors used in the Republic of Serbia (305,000) 56.12% falls into this category [23]. These tractors make 67% in the total fuel consumption by agricultural machinery. Thus, the aim of this research is to give an objective evaluation of the effects of use of biodiesel and fossil diesel blends on the performances and exhaust gas emissions of medium power tractors.

In the Republic of Serbia biodiesel can be produced from sunflower which is the most common oilseed crop. The land area of 174.331 ha is covered with sunflower producing the average yield of 2.09 t/ha [24]. Favorable climatic conditions, long tradition, mastered production technology and large number of domestically produced hybrids are all advantages for the sunflower production. Other advantages of sunflower are high energy value of sunflower cake and good sources of protein with amino acid availabilities similar to those of soybean meal. Also, sunflower meal does not have anti-nutritional factors such as those found in soybean and rapeseed meals [25].

Materials and methods

Fuels

Biodiesel blending was carried out in the following ratios during the analysis: 85:15%(v/v) fossil diesel-methyl ester (BD-15), 75:25%(v/v) (BD-25), 50:50%(v/v) (BD-50), 25:75%(v/v) (BD-75), and 0:100% (BD-100). The results were compared with the commercial fossil diesel. Methyl ester (biodiesel) was obtained by the process of transesterification of sunflower oil in methyl alcohol in the presence of NaOH that was used as a catalyst.

Domestic sunflower hybrid "Somborac" was used in the research. It is a medium late hybrid which matures in the period of 107-113 days. The genetic potential for seed yield is 4.6 t/ha. Oil content in the seed is 48-51%. Prior to the tests, the analysis of biodiesel compliance with the standard EN 14214 was performed. Results of the analysis indicate that the used biodiesel is in line with EN 14214 standard (tab. 1).

Table 1. Properties of used biodiesel (SRPS EN 14214:2009)

Property	Units	Limit	Value	Method
Ester content	$(m \cdot m^{-1})\%$	min 96.5	99.71	EN 14103
Density at 10 °C	kgm^{-3}	860-900	884	EN ISO 3675
Kinematic viscosity at 40 °C	mm^2s^{-1}	3.5-5.0	3.93	EN ISO 3104
Flash point (Pensky-Martens)	°C	min 101	154	EN ISO 3104
Cold filter plugging point (CFPP) – Climate classes C	°C	max –5	–4	SRPS EN 116
Sulfur content	$mgkg^{-1}$	max 10	0.81	EN ISO 20846
Carbon residue remnant (at 10% distillation remnant)	$(m \cdot m^{-1})\%$	max 0.3	0.19	EN ISO 10370
Sulfated ash content	$(m \cdot m^{-1})\%$	max 0.02	0.0	ISO 3987
Water content	$mgkg^{-1}$	max 500	279	EN ISO 12937
Cetan index	–	>51	51.8	SRPS ISO 4264
Total contamination	$mgkg^{-1}$	max 24	0.1	EN 12662
Copper band corrosion (3 h at 50 °C)	Class	1	1a	EN ISO 2160
Acid value	$mgKOHg^{-1}$	max 0.5	0.2	EN 14104
Linolenic acid methylester	$(m \cdot m^{-1})\%$	max 12	6.31	EN 14103
Polyunsaturated (>=3 double bonds metylester)	$(m \cdot m^{-1})\%$	max 1	<0.02	SRPS EN15779
Methanol content	$(m \cdot m^{-1})\%$	max 0.2	0.008	EN 14110
Monoglyceride content	$(m \cdot m^{-1})\%$	max 0.8	0.163	EN 14105
Diglyceride content	$(m \cdot m^{-1})\%$	max 0.2	0.028	EN 14105
Triglyceride content	$(m \cdot m^{-1})\%$	max 0.2	0.065	EN 14105
Free glycerine	$(m \cdot m^{-1})\%$	max 0.02	0.0004	EN 14105
Total glycerine	$(m \cdot m^{-1})\%$	max 0.25	0.0527	EN 14105
Group I metals (Na + K) Group II metals (Ca + Mg)	$mgkg^{-1}$	max 5	4.708 3.044	EN 14108 EN 14538
Phosphorus content	$mgkg^{-1}$	max 4	2.61	EN 14107
High heating value	$MJkg^{-1}$	–	40.348	ASTM D5865-07

Biodiesel was blended with low sulfur fossil diesel produced in the oil refinery from Novi Sad (hereinafter LSDF)[*]. Results of the analysis of the used LSDF indicate that this fuel is in line with SRPS EN 590 (tab. 2).

Table 2. Properties of used fossil diesel (SRPS EN 590:2010)

Property	Units	Value	Method	Property	Units	Value	Method
Density at 15 °C	kgm^{-3}	838.3	SRPS ISO 12185	Distillation at 250 °C	v·v^{-1}	45.2	SRPS EN ISO 3405
IBP	°C	171.5	SRPS EN ISO 3405	Distillation at 350 °C	v·v^{-1}	95.9	
10%	°C	202.9		Viscosity	mm^{2}s^{-1}	3.01	SRPS ISO 3104
20%	°C	216.5		Flash point	°C	65	SRPS EN ISO 2719
30%	°C	229.7		Blur point	°C	–5	SRPS ISO 3015
40%	°C	243.5		Cold filter plugging point	°C	–19	EN 116
50%	°C	255.7		Sulfur content	mgkg^{-1}	8.2	ASTM D 5453
60%	°C	269.2		Water content	mgkg^{-1}	60	SRPS ISO 12937
70%	°C	284.1		Cetane index	–	49.7	SRPS ISO 4264
80%	°C	301.8		Copper band corrosion	3 h at 50 °C	1a	SRPS ISO 2160
90%	°C	326.1		Total contamination	mgkg^{-1}	/	SRPS EN 12662
95%	°C	345.5		Appearance	–	Clear	Visual
FBP	°C	362.7		Color	–	0.5	SRPS ISO 2049
Rest	%v·v^{-1}	0.8		Oxidation stability	gm^{-3}	/	SRPS ISO 12205
Loss	%v·v^{-1}	0.9		Polycyclic aromatic hydrocarbons	%m·m^{-1}	6.6	FOX (MIDAC)
				High heating value	MJkg^{-1}	46.291	ASTM D5865-07

Table 3. shows main properties of biodiesel and LSDF blends used in the reserach.

Engine and instruments

Engine characteristics and exhaust gas emissions of the tested fuels were analyzed for the tractor type Mahindra 6500 4WD. Tractor type Mahindra 6500 is the all purpose tractor (a four-wheel-drive tractor with smaller steering wheels at the front), intended for performing various operations in agriculture (basic tillage, presowing preparation, sowing, mechanical and chemical crop care, transport ...) in small farmsteads

Table 3. Properties of used blends of biodiesel and LSDF

Property	Units	Value			
		BD-15	BD-25	BD-50	BD-75
Density 15 °C	kgm^{-3}	845.2	849.7	861.1	872.6
Viscosity	mm^{2}s^{-1}	3.128	3.214	3.439	3.679
Flash point	°C	92	98	114	132
Sulfur content	mgkg^{-1}	7.2	6.4	4.5	2.7
Water content	mgkg^{-1}	143	171	219	253
High heating value	MJkg^{-1}	45.386	44.828	43.288	41.701

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[*] LSDF – Low sulfur diesel fuel

which are most common in the Republic of Serbia. The tractors were equipped with Mahindra NE 462R four-cylinder, DI, four stroke with a bore of 96 mm, a stroke of 122 mm, a displacement of 3532 cm^3, compression ratio of 19.5:1, rated power of 48.4 kW at 2200 rpm, and a maximum torque of 217.4 Nm at 1398 rpm. This tractor engine is of Tier II generation type. Fuel injection pump is the MICO Bosch (VE Type). Fuel injection pump is a single plunger, rotary distributor pipe pump incorporating a centrifugal spill port governor. Fuel injection pressure 250-258 bars.

The tractor engine was connected to the electric Eggers dynamometer type 301/ME through the power take-off shaft (accuracy level <1%, fig. 1). Fuel consumption was measured by the volume method applying the flowmeter Pierburg 2911 (accuracy level ±0.5%). Exhaust gas emissions (NO_x, CO, CO_2, accuracy level 2 ppm, 2 ppm, ±0.2% vol., respectively) were measured by Testo 355 portable analyzer (Testo GMBH, Lenzkirch, Germany). The temperatures of cooling liquid and engine oil, temperature of air at the entrance to the suction pipe, and the fuel temperature were measured by thermocouple LM-35 (accuracy level ±0.5%), HBM – Hottinger Baldwin Messtechnik, Germany. The ambient conditions (temperature, pressure and relative air humidity) were measured by the device GFTB-100, Greisinger electronic GmbH, Germany (accuracy level ±0.1 °C, 0.1 mbar, 0.1% r.F). The number of revolutions was measured by digital tachometer Testo type 0563 4710 (accuracy level ±0.02%).

The tests were conducted in the registered OECD Laboratory for Power Machines and Tractors (LMT) from Novi Sad, Serbia.

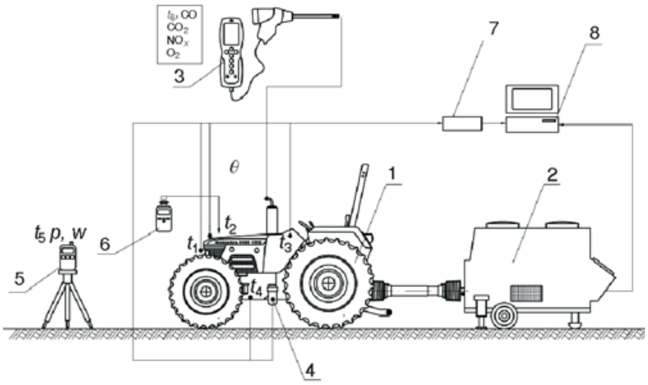

Figure 1. The scheme of measuring equipment
1 – tested tractor, 2 – dynamometer Eggers 301/MEM, 3 – exhaust gas analyzer Testo 335, 4 – fuel flowmeter Pierburg 2911, 5 – ambient conditions measuring instrument, 6 – engine speed gauge, 7 – acquisition (Spider 8), 8 – PC, t_1 *– suction air temperature,* t_2 *– cooling liquid temperature,* t_3 *– fuel temperature,* t_4 *– engine oil temperature,* t_5 *– outside temperature,* t_6 *– exhaust gases temperature*

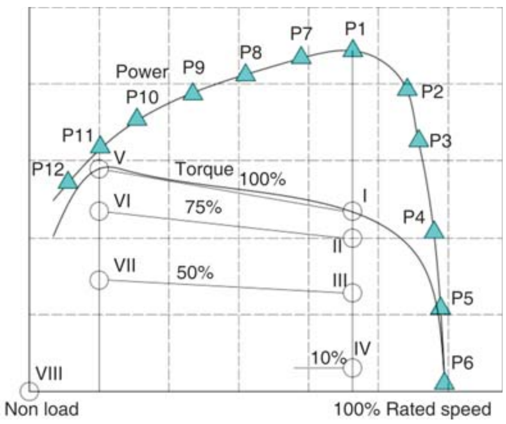

Figure 2. Operation points of CODE 2 and ISO 8178-4, C1 (8-point cycle)

Experimental procedure

The performances of the engine using different fuel types (part *Fuels*) were evaluated in compliance with the OECD standard (CODE 2) for the purpose of the official testing of agricultural tractors [26]. The testing first included 6 points of the governor control of curve, with full load (fig. 2, points are marked with triangles). Point P1 represents the rated power. Point P2 is the power at a torque of 85% which is achieved in the point P1. Point P3 is the power at a torque of 75% achieved in the point P2. Point P4 is the power at a torque of 50% achieved in the point P2. Point P5 is the power at a torque of 25% achieved in the point P2. Point P6 represents the characteristics of unloaded engine [27].

In addition to the points on the governer control curve, the measuring also included the part of the curve from point P1 to the maximum torque. During the testing, points in this part of the curve were measured at every 200 rpm (P7- value measured at 2000 rpm, P8-1800 rpm, P9-1600 rpm, P10-1400 rpm, P11-value measured at maximum torque, and P12-1200 rpm).

Exhaust gas emissions were measured in compliance with the standard ISO 8178-4, C1 (8-point cycle) [28]. Point I (fig. 2, points are marked with circles) was obtained in the regime of maximum power at the rated speed. Point II is the point at a torque of 75% achieved in the point I and at rated speed. Point III is at a torque of 50% achieved in point I and at rated speed. Point IV is the point with loaded engine at a torque of 10% achieved in point I and at rated speed. Point V represents the operating regime at peak torque. Point VI is the operating regime at peak torque of 75% and at the number of revolutions which corresponds to the peak torque. Point VII is the operating regime at peak torque of 50% and number of revolutions which corresponds to the peak torque. Point VIII is the operating regime of the unloaded engine at idle speed.

Statistical analyses were carried out as one-way ANOVA with one fixed factor (fuel blend). The values represent average values of 6 measurings performed in one hour. Differences between mean values for different engine performance variables considered were tested by the Duncan's interval test ($P < 0.01$) [26]. All statistical analyses were performed using the Statistica 10 software package.

Results and discussion

Engine performance

Engine performance, torque, power, specific fuel consumption and thermal efficiency are given in fig. 3 for all tested fuels with respect to the number of revolutions of the crankshaft.

The use of LSDF produced rated power of 44.01 kW at 2200 rpm. The test fuels BD-15, BD-25, BD-50, BD-75, and BD-100 produced the rated power of 44.25, 42.85, 42.26, 41.41, and 41.21 kW, respectively. In comparison to the LSDF the test fuels BD-15, BD-25, BD-50, BD-75, and BD-100 had lower power by -1.51, 1.21, 2.86, 5.36, and 5.74%, respectively, for the entire measuring range.

Although the used biodiesel had lower heating value than the LSDF (by 12.84%), test fuel BD-15 showed an increase of 0.54% at rated power with respect to the LSDF, and for the entire measuring range that increase was 1.51%. This power increase complies with the results of other authors [29] which could be explained in different ways. Namely, high content of oxygen in biodiesel fuel (about 11%) [12] enables more complete combustion. Also, fuel density is increased by blending biodiesel with fossil diesel. Considering the fact that the fuel injection pump is voluminous more fuel mass can flow in the same volume which further results in more engine power. The third reason for power increase is kinematic viscosity (kinematic viscosity of fuel BD-15 was 3.9% higher than that of the LSDF). Apart from the negative effect of increased kinematic viscosity on the atomization process and air-fuel mixing, a slight increase can affect positively the engine performances since it enables less internal fuel leakage (between the pump and syringe elements) [30].

Table 4. Engine power [kW] for different fuel blends and different OECD engine testing points

	P 1[1]		P2		P3		P4		P5		P6		P7		P8		P9		P10		P11		P12		Mean	
LSDF	44.01	a[2]	40.61	b	31.15	a	21.06	a	10.59	b	4.35	a	42.27	b	40.52	ab	38.83	a	36.79	a	35.26	a	28.47	a	28.68	a
BD 15	44.25	a	41.68	a	31.41	a	21.44	a	10.89	a	4.39	a	43.85	a	41.17	a	38.08	ab	35.69	bc	34.51	b	28.15	a	28.69	a
BD 25	42.85	b	39.97	b	31.17	a	21.01	a	10.64	b	4.30	a	42.20	b	39.77	bc	38.43	ab	36.31	ab	34.31	bc	28.27	a	28.36	b
BD 50	42.26	b	40.22	b	29.92	b	20.53	b	10.22	c	4.29	a	41.96	bc	39.10	cd	37.97	bc	34.77	bc	33.57	bc	27.89	a	27.81	c
BD 75	41.41	c	38.96	c	29.56	b	19.47	c	9.94	d	4.29	a	41.37	bc	38.50	d	37.61	bc	35.73	cd	33.99	bc	26.74	b	27.51	d
BD 100	41.21	c	38.95	c	29.54	b	19.423	c	9.80	d	4.13	b	41.38	c	38.38	d	37.37	c	35.40	d	34.20	c	26.58	b	27.37	d
Mean	42.66		40.07		30.46		20.49		10.35		4.29		42.12		39.57		38.05		35.78		34.31		27.68			

Table 5. Specific fuel consumption [$gkW^{-1}h^{-1}$] for different fuel blends and different OECD engine testing points

	P 1[1]		P2		P3		P4		P5		P6		P7		P8		P9		P10		P11		P12		Mean	
LSDF	277.7	d[2]	271.3	d	322.8	bc	375.9	b	469.2	d	1114.9	c	267.1	d	266.7	d	256.2	c	246.3	b	247.4	d	219.1	d	363.4	e
BD 15	279.2	d	272.1	d	327.5	b	380.1	b	497.0	d	1121.7	c	268.2	d	267.5	d	264.7	b	256.8	a	264.5	a	219.1	d	368.2	d
BD 25	285.3	c	276.0	cd	315.9	c	392.6	a	489.1	d	1159.3	c	271.7	d	275.7	c	250.9	c	237.5	c	256.5	bc	227.5	c	369.8	d
BD 50	302.4	b	278.1	c	320.1	bc	407.7	a	547.8	c	1109.6	b	280.3	c	285.1	b	270.5	a	248.2	b	251.9	cd	211.4	e	376.1	c
BD 75	315.8	a	296.8	b	318.3	c	447.4	a	610.4	b	1175.4	b	289.7	b	279.8	bc	267.9	ab	238.9	c	255.1	bc	238.3	b	394.5	b
BD 100	313.6	a	306.8	a	346.2	a	456.9	a	642.5	a	1237.8	a	296.9	a	301.7	a	277.1	a	252.2	ab	260.6	ab	256.1	a	411.9	a
Mean	295.7		283.5		325.2		410.1		547.1		279.0		279.0		279.4		263.6		246.6		256.0		228.6			

Table 6. Thermal efficiency for different fuel blends and different OECD engine testing points

	P 1[1]		P2		P3		P4		P5		P6		P7		P8		P9		P10		P11		P12		Mean	
LSDF	0.280	a[2]	0.287	b	0.241	c	0.207	a	0.157	b	0.070	d	0.291	b	0.292	b	0.304	cd	0.316	c	0.314	c	0.355	c	0.256	c
BD 15	0.284	a	0.291	b	0.242	c	0.209	a	0.160	b	0.071	cd	0.296	ab	0.297	b	0.300	d	0.309	c	0.300	d	0.362	b	0.256	c
BD 25	0.281	a	0.291	b	0.254	b	0.205	a	0.164	a	0.069	d	0.295	ab	0.291	b	0.320	b	0.338	b	0.313	c	0.355	c	0.261	b
BD 50	0.275	b	0.299	a	0.260	b	0.204	a	0.152	c	0.075	a	0.297	ab	0.292	b	0.307	c	0.335	b	0.338	b	0.392	a	0.265	a
BD 75	0.273	b	0.291	b	0.271	a	0.193	b	0.141	d	0.073	ab	0.298	a	0.309	a	0.332	b	0.361	a	0.330	a	0.362	b	0.267	a
BD 100	0.284	a	0.291	b	0.258	b	0.195	b	0.139	d	0.072	bc	0.300	a	0.296	b	0.329	a	0.354	a	0.342	a	0.348	c	0.264	a
Mean	0.280		0.292		0.254		0.202		0.152		0.072		0.296		0.296		0.314		0.335		0.323		0.362			

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[1] P1 – rated power, P2 – value at 85% of torque achieved in the point P_1, P3 – value at 75% of torque achieved in the point P_2, P4 – value at 50% of torque achieved in the point P_2, P5 – value at 25% of torque achieved in the Point P_2, P6 – unloaded engine, P7 – value measured at 2000 rpm, P8 – 1800 rpm, P9 – 1600 rpm, P10 – 1400 rpm, P11 – value measured at maximum torque, P12 – 1200 rpm.

[2] Ranking of the value in the same column. There is no statistically significant difference at significance threshold of 0.01 between the values marked with the same letter in one column n.

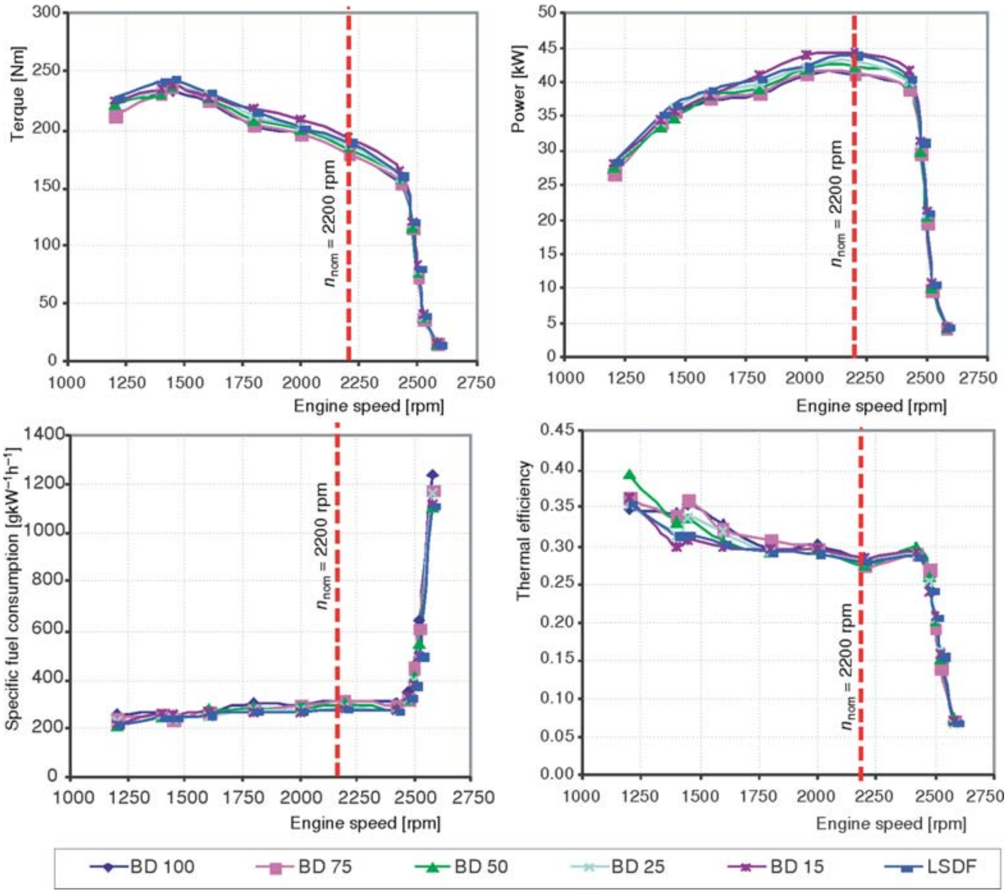

Figure 3. Power characteristics of the engine with different test fuels

Table 4 shows average power values (the average of 6 measurements) for 12 points and all tested fuels. Letters in the table represent the ranking of the obtained values for the measuring points. The same letters in one column indicate that the values are of the same ranking, that is, that there is no statistically significant difference between the obtained values for the significance threshold of 0.01.

The ANOVA analysis indicated that all tested fuels had high statistically significant power differences ($p = 0.00$) for the entire measuring range $(\overline{P}_i, i = 1, 2 \ldots 12)$. The Duncan's test showed high statistically significant power differences in all fuel types except for the LSDF and BD-15, and BD-75 and BD-100 which showed no statistically significant differences.

The lowest specific fuel consumption was recorded with the LSDF while the BD-100 fuel had the highest fuel consumption. With respect to the LSDF, the test fuels BD-15, BD-25, BD-50, BD-75, and BD-100 had higher specific fuel consumption by 1.32, 1.76, 3.49, 8.56, and 13.35%, respectively, for the entire measuring range. Low heating value and high fuel density are the reasons for such increase in the specific fuel consumption. Given that the heating value of fuel BD-15, BD-25, BD-50, BD-75, and BD-100 less than the LSDF for 1.96, 3.16, 6.49, 9.92, and 12.84%, respectively, it can be concluded that the combustion of a mixture biodiesel and fossil diesel fuel is more completely.

According to the ANOVA it was concluded that all tested fuels had high statistically significant differences in the specific fuel consumption ($p = 0.00$) for the entire measuring range ($\bar{P}_i, i = 1, 2 \ldots 12$). The Duncan's test showed high statistically significant differences in specific fuel consumption between all fuel types except for BD-15 and BD-25 which showed no statistically significant differences (tab. 5).

Average value of thermal efficiency was 0.256 for the LSDF for the entire measuring range ($\bar{P}_i, i = 1, 2 \ldots 12$). With respect to the LSDF, the test fuels BD-15, BD-25, BD-50, BD-75, and BD-100 had higher thermal efficiency by 0, 1.95, 3.52, 4.29, and 3.13%, respectively, for the entire measuring range. The highest values of this parameter were achieved by using the fuel type BD-75. All fuel types showed higher thermal efficiency value with the increase of engine load.

Based on the ANOVA it was concluded that all tested fuels had high statistically significant differences in thermal efficiency ($p = 0.00$) for the entire measuring range ($\bar{P}_i, i = 1, 2 \ldots 17$). The Duncan's test showed high statistically significant differences between the following pairs: LSDF and BD-25, LSDF and BD-50, LSDF and BD-75, LSDF and BD-100, BD-50 and BD-15, BD-50 and BD-25, and between BD-25 and all other fuels (tab. 6)

In spite of the reduced heating value and increased specific fuel consumption, thermal efficiency was increased in all fuels with high biodiesel content which enabled more complete combustion. Similar results were recorded in the study with low power engines of 7.5 kW when thermal efficiency was improved with blends BD-20 and BD-30 [31]. Canacki and Van Gerpen [32] observed that biodiesel was injected earlier in comparison to the fossil diesel fuel. When injected earlier biodiesel is also combusted earlier which improves thermal efficiency. Also, higher biodiesel cetane number causes shorter delay time of fuel combustion and provides more time for complete combustion [31, 33].

Exhaust gas emissions

Analysis of exhaust gas emission included the emissions of CO_2, CO, and NO_x, and the temperature of exhaust gases.

The CO_2 emissions

The diagram (fig. 4) shows the CO_2 emissions based on the change of engine load for all test fuels. The CO_2 emission from all test fuels increased with the engine load increase. In comparison to fossil diesel, the fuel types BD-15, BD-25, BD-50, BD-75, and BD-100 caused the reduction of CO_2 emission by, on average, 2.05, 5.01, 5.91, 7.70, and 8.99%, respectively.

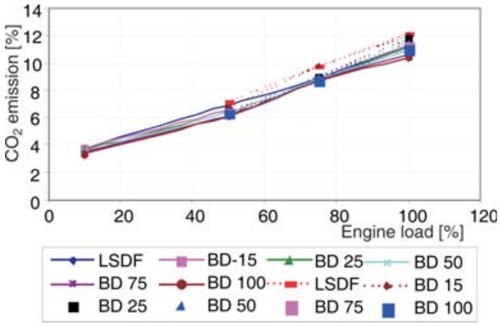

Figure 4. Variation of CO_2 with engine load for different fuels; (—– rated speed, 2200 rpm, - - - engine speed at max. torque)

Figure 5 shows the relative change in the CO_2 emission with respect to LSDF. The emission variations occurred with different test fuels and for different ISO 8178-4 standard and C1 engine test points. The diagram also shows that the increased biodiesel share in fossil diesel causes the reduction of CO_2 emission at lower engine load. This further leads to a decrease in the combustion efficiency. The main reason for this is high kinematic viscosity with high biodiesel content. Namely, a minor increase of kinematic viscosity has positive effect on the engine performances due to the low internal fuel leakage. However, it has negative effect on the atomization process, air-fuel mixing and the quality of combustion of the formed blend [34]. Also, some authors [35-39] explain the reduced CO_2 emission with lower content of elementary carbon and hydrogen in biodiesel with respect to fossil diesel fuel.

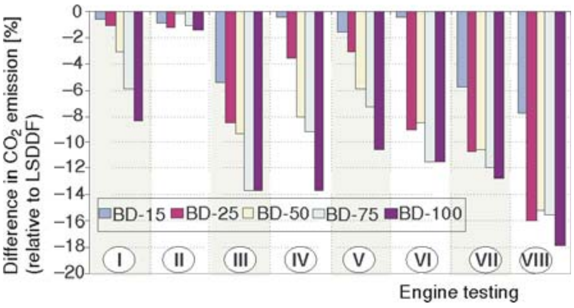

Figure 5. Percentage change of the CO_2 emission (relative to LSDF)

According to the ANOVA it was concluded that all tested fuels gave high statistically significant differences ($p = 0.00$) in the CO_2 emissions for the entire measuring range ($\overline{P}_i, i = 1, 2...8$). Duncan's test showed statistically significant differences in the CO_2 emission for all tested fuels except for BD-25 and BD-50 which showed no statistically significant difference (tab. 7).

The NO_x emissions

The conducted researches showed that higher engine load caused linear increase of NO_x emission in all test fuels at rated speed, fig. 6 (a). The highest NO_x emission was measured in the point P-VI. On the other hand, specific NO_x emission was reduced in all test fuels as the engine load increased. The load increase of 50% at rated speed did not cause any changes in the specific NO_x emission, fig. 6(b).

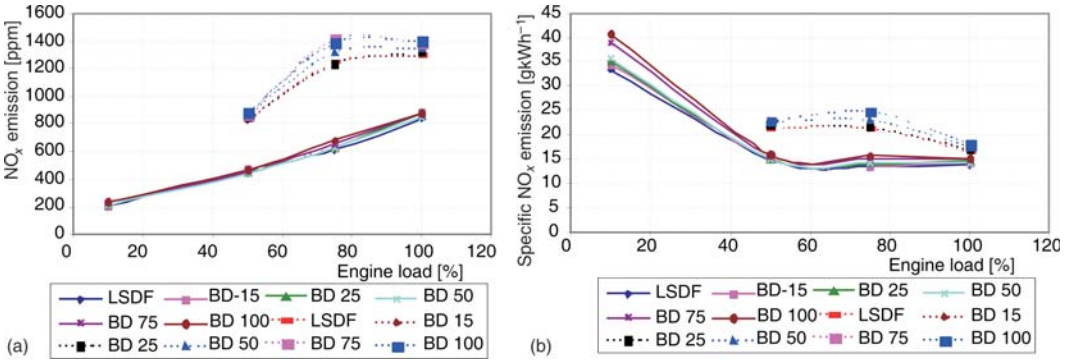

Figure 6. Variation of NO_x with engine load for different fuels (a) in ppm, (b) in g/kWh; (— – rated speed, 2200 rpm, - - - engine speed at max torque)

The increased share of biodiesel in the blend causes high NO_x emission, fig. 7. In comparison to LSDF, the fuel types BD-15, BD-25, BD-50, BD-75, and BD-100 had higher NO_x emission by, on average, 1.51, 3.10, 4.89, 9,50, and 11.38%, respectively. The results obtained from this study are similar to those stated by EPA (Environmental Protection Agency) [40].

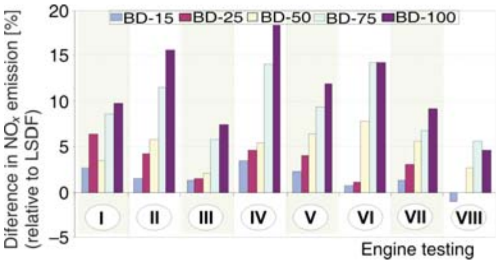

Figure 7. Percentage change of the NO_x emission (relative to cLSDF)

According to the EPA the use of BD-20 leads to an increase in the NO_x emission by 2% in comparison to fossil diesel.

According to the ANOVA it was concluded that all tested fuels had high statistically significant differences ($p = 0.00$) in the NO_x emissions for the entire measuring range $(\overline{P}_i, i = 1, 2 \ldots 8)$. Duncan's test showed high statistically significant differences in the NO_x emission for all tested fuels except for the LSDF, BD-15, and BD-25 and between BD-75 and BD-100 (tab. 8).

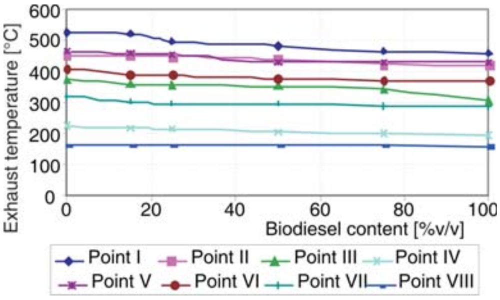

Figure 8. Change of the exhaust gases temperature depending on the biodiesel content

Table 7. CO_2 emissions (%) for different fuel blends and different ISO 8178-4, C1 engine testing points

	P I[1]		PII		PIII		PIV		PV		PVI		PVII		PVIII		Mean	
LSDF	11.30	a[2]	8.80	a	6.96	a	3.80	a	12.18	a	9.80	a	7.16	a	2.31	a	7.79	a
BD 15	11.24	a	8.72	a	6.60	b	3.78	a	12.00	ab	9.76	a	6.77	b	2.15	b	7.63	b
BD 25	11.28	a	869	a	6.41	c	3.67	b	11.83	b	8.99	b	6.47	c	1.99	c	7.40	c
BD 50	10.96	b	8.79	a	6.37	c	3.52	c	11.51	c	9.03	b	6.47	c	2.01	c	7.33	c
BD 75	10.68	c	8.71	a	6.13	d	3.48	c	11.35	c	8.79	b	6.39	c	2.00	c	7.19	d
BD 100	10.44	d	8.68	a	6.12	d	3.34	d	11.01	d	8.87	b	6.35	c	1.96	c	7.09	e
Mean	10.96		8.73		6.43		3.60		11.65		9.19		6.60		2.07			

Table 8. NO_x emissions (g/kWh) for different fuel blends and different ISO 8178-4, C1 engine testing points

	P I[1]		PII		PIII		PIV		PV		PVI		PVII		PVIII		Mean	
LSDF	13.76	d[2]	13.37	d	14.71	b	33.26	e	16.50	e	21.22	c	21.29	d	742.32	c	7.79	c
BD 15	14.15	c	13.56	d	14.92	b	34.50	d	16.89	de	21.36	c	21.59	d	734.57	c	7.63	c
BD 25	14.71	b	13.95	c	14.93	b	34.98	cd	17.18	d	21.46	c	21.97	c	741.86	c	7.40	c
BD 50	14.28	c	14.19	c	15.02	b	35.59	c	17.62	c	23.02	b	22.56	b	763.49	b	7.33	b
BD 75	15.04	a	15.11	b	15.85	a	38.91	b	18.20	b	24.76	a	22.86	b	786.92	a	7.19	a
BD 100	15.29	a	15.78	a	15.98	a	40.70	a	18.72	a	4.722	a	23.46	a	777.83	b	7.09	a
Mean	14.54		14.33		15.23		36.33		17.52		22.76		6.60		757.83			

Table 9. The CO emissions (g/kWh) for different fuel blends and different ISO 8178-4, C1 engine testing points

	P I[1]		PII		PIII		PIV		PV		PVI		PVII		PVIII		Mean	
LSDF	1.89	a[2]	2.03	a	2.32	a	10.37	a	1.32	a	0.59	a	0.97	a	119.78	a	17.41	a
BD 15	1.64	b	1.86	b	2.19	b	9.97	b	1.27	b	0.55	b	0.97	a	118.23	a	17.09	b
BD 25	1.62	b	1.74	c	2.13	c	9.82	b	1.22	c	0.53	c	0.96	a	116.00	b	16.75	c
BD 50	1.42	c	1.67	d	2.08	c	9.59	c	1.08	d	0.49	d	0.88	b	109.11	c	15.79	d
BD 75	1.36	d	1.52	e	1.98	d	9.36	d	1.08	d	0.42	e	0.85	c	106.77	d	15.42	e
BD 100	1.34	d	1.43	f	1.68	e	9.27	d	0.97	e	0.40	f	0.82	d	105.04	d	15.2	f
Mean	1.54		1.71		2.06		9.73		1.15		0.50		0.91		112.49			

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[1] P I – emission at maximum power and rated speed, P II – emission at 75% of torque achieved in the point I and at rated speed, P III – emission at 50% of torque achieved in the point I and at rated speed, P IV – emission at 10% of torque achieved in the point I and at rated speed, P V – emission at max. torque, P VI – emission at 75% of max. torque at number of revolutions corresponding to the max. torque, P VII – emission at 50% of max. torque at number of revolutions corresponding to the max. torque, P VIII – emission from the unloaded engine at idle speed.

[2] ranking of the value in the same column. There is no statistically significant difference at significance threshold of 0.01 between the values marked with the same letter in one column

The NO_x emission is conditioned by the combustion temperature, oxygen concentration, peak pressure, and time [41]. Figure 8 shows the exhaust gases temperatures based on the changes of the share of biodiesel in the blend. Figure 9 shows the change of NO_x emission based on the change of the oxygen concentration in the combustion products. It is already known that the NO_x emission increases as the temperature of combustion products increases. Since the increased content of biodiesel in LSDF reduces the exhaust gas temperatures, then the increased emission of NO_x is most probably the consequence of characteristics of raw materials used for biodiesel production. Namely, Lapuerto *et al*. [42] states that NO_x emission is affected by iodine number. According to the results from these research, NO_x emission will be the same as from fossil diesel fuel by using biodiesel with iodine number below 50 which can be achieved with biodiesel produced from pig fat (iodine number of pig fat is 46-66). On the other hand, sunflower oil has iodine number of 118-141 (the iodine number of tested biodiesel was 132).

The reason for high NO_x emission lies in the high content of oleic acid in biodiesel produced from sunflower oil (over 64%). Knothe [43] investigated the NO_x emission from fossil diesel fuel and biodiesel with different content of fatty acids. The authors concluded that biodiesel with high content of palmitic methyl ester (C 16:0) and lauric methyl ester (C 12:0) had lower content of NO_x in comparison to the fossil diesel fuel. However, they concluded that high content of oleic methyl ester (C 18:1) in biodiesel increased the NO_x emission.

The CO emissions

The increase in load leads to the increase of the CO emission which is the consequence of air excess ratio reduction in the engine cylinder, fig. 9. The conducted research showed that the highest CO concentrations were emitted by using the LSDF, and the lowest emissions occurred with the use of BD-100. In comparison to the LSDF, the test fuels BD-15, BD-25, BD-50, BD-75 and BD-100 caused the reduction in CO emission by, on average, 1.84, 3.79, 9.30, 11.43, and 13.15%, respectively, fig. 10, tab. 9. With an increase in the engine load the specific emission of CO is considerably reduced by using the fuels with higher content of biodiesel. Conversely, this difference is proportionally small with the low engine load. The reason for this lies in the fact that the fuel with high biodiesel content has higher kinematic viscosity in comparison to the LSDF. Therefore, low load and low temperature in the engine cylinder cause poor atomization and air-fuel mixing. On the other hand, increased load leads to the higher temperature of

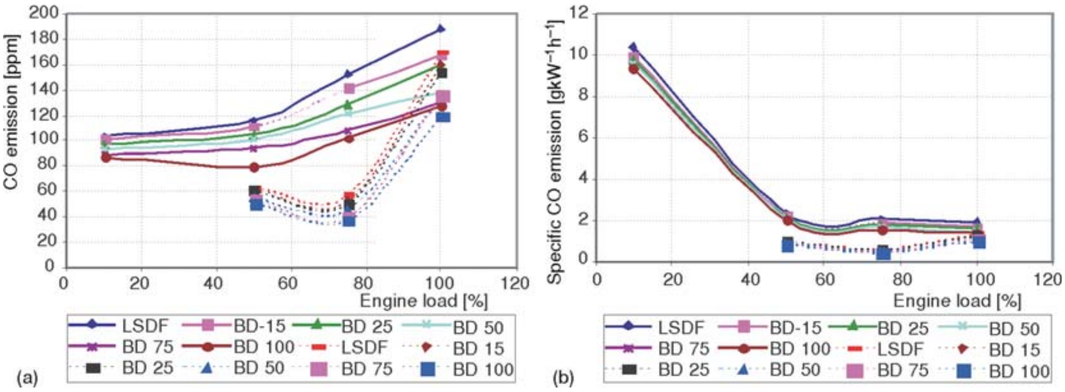

Figure 9. Variation of CO with engine load for different fuels (a) in ppm, (b) in g/kWh (—– rated speed, 2200 rpm, - - - engine speed at max torque)

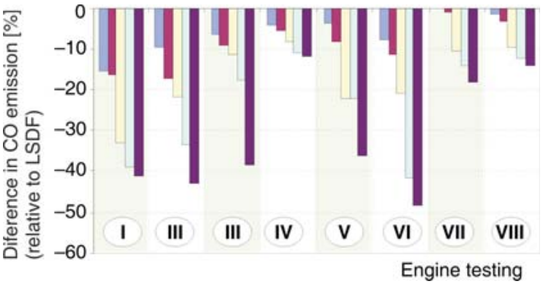

Figure 10. Percentage change of the CO emission (relative to cLSDF)

the engine cylinder which results in better fuel atomization. All the previously mentioned further results in better air-fuel mixing, better combustion, and reduction of the CO emission [26, 44]. Besides the poor atomization, the use of biodiesel at low load reduces the CO emission in comparison to LSDF. This is caused by higher content of oxygen in biodiesel which facilitates the combustion process [35].

Based on the ANOVA it was concluded that there were high statistically significant differences in the CO emissions ($p = 0.00$) from different fuel types for the entire measuring range ($\overline{P}_{i,}\, i = 1, 2\ldots8$). Duncan's test showed statistically significant differences in the CO emissions from all fuel types.

Conclusions

The experimental research has been conducted with the aim of determining the objective possibilities of using biodiesel from sunflower in the engines of medium power agricultural tractors. Therefore, engine performances and exhaust gas emissions were compared by using pure biodiesel, fossil diesel, and blends of fossil diesel with 15, 25, 50, and 75%v/v biodiesel. Based on the results, the following conclusions can be drawn.

- In comparison to fossil diesel, biodiesel increase in the blend leads to the power reduction which results in the low heating value of biodiesel and high kinematic viscosity. The BD-15 fuel represents an exception since it showed slight increase of power in comparison to other fuels, including the fossil diesel fuel.
- As biodiesel increases in the blends, the specific fuel consumption for all tested fuels also increases in comparison to fossil diesel. However, the increase in specific fuel consumption, which occurrs as a result of blending biodiesel with fossil diesel, is lower than the decrease in heating value. This is the result of higher density and lower biodiesel heating value in comparison to fossil diesel fuel.
- Thermal efficiency slightly increases with the increase of biodiesel share in the blend, which is the result of faster and more complete fuel combustion.
- The increase of biodiesel in the blend leads to the reduction of CO_2 and CO emissions. With higher loads CO_2 emission is reduced less than the CO emission. This is the result of more complete fuel combustion at higher engine load.
- The increase of biodiesel share in the blends leads to the reduction of exhaust gas temperatures in all operation regimes. At lower exhaust gas temperatures NO_x emission still increases with an increase of biodiesel. This is the result of increased oxygen content in the combustion products.

Acknowledgments

This work was supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia (project: Improvement of the quality of tractors and mobile systems with the aim of increasing competitiveness and preserving soil and environment, No TR-31046).

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Paper submitted: November 22, 2011
Paper revised: March 3, 2012
Paper accepted: April 16, 2012