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Effect of sunflower and rapeseed oil on production of solid particles and performance of diesel engine

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Abstract. The development of biofuels for compression ignition engines is heading primarily to utilization of vegetable oils. Combusting of 100% vegetable oil in unmodified CI engine is usually not possible due to higher viscosity of the vegetable oil. In order to use 100% vegetable oil in CI engine the oil needs to be preheated, esterified or hydrotreated. Alternatively, in order to use raw vegetable oil in CI engine without preheating it is possible to use vegetable oil – diesel fuel blends or vegetable oil – butanol – diesel fuel blends in order to lower the viscosity of the fuel. The contribution focuses on comparison of the effect of sunflower and rapeseed vegetable oils on operational parameters of the turbocharged compression ignition engine, especially on production of solid particles. The measurement was carried out according to standardized NRSC test cycle. 5% and 20% concentration of vegetable oils in diesel fuel were used as a test fuels for the measurement while the diesel fuel was used as a reference. The count and size of solid particles were measured by means of EEPS particle analyser. Based on the measured values it can be stated that the slight increase of performance parameters occurred with strong effect on emissions production, especially on production of solid particles.

Key words: Combustion engine, biofuels, diesel fuel, particulate matter, vegetable oil, fuel blend.

INTRODUCTION

The biofuels in the combustion engines are used to reduce the impact of combustion of fossil fuels on the atmosphere and to reduce dependency on fossil fuel products. The biofuels based on vegetable oils or alcohols are most commonly used for CI (Compression Ignition) engine (Jindra et al., 2016; Kumar et al., 2016; Kumar & Saravanan, 2016; Gailis et al., 2017; How et al., 2018). For this purpose the edible and non-edible oils from a variety of plants with suitable oil characteristics can be used (Vanichseni et al., 2003; Sidibé et al., 2010; No, 2011; Mat et al., 2018; Shah et al., 2018).

In comparison with the diesel fuel the vegetable oil is denser and has a higher viscosity, higher flash point, lower calorific value, higher surface tension, higher oxygen content and lower carbon content (Franco & Nguyen, 2011; Esteban et al., 2012).

Utilization of the 100% vegetable oil as a fuel for compression ignition engine requires modification of the fuel system because it is necessary to preheat the oil in order to reduce the viscosity (Pexa et. al., 2014). The recommended temperature for oil preheating varies significantly, the values, published by other authors, are in the range from 70 °C (Kumar et al., 2005) to 135 °C (Pugazhvadivu & Jeyachandran, 2005). Vegetable oil may be also used as an admixture to the diesel fuel or other fuel blends (Franco & Nguyen, 2011). Raw vegetable oil can be added into the diesel fuel in ratio 20% oil and 80% diesel fuel and it can be burned without modification of the engine or preheating of the fuel (Elango & Senthilkumar, 2011; Yilmaz & Morton, 2011; Gad et al., 2017; Mat et al., 2018), some sources state 30% of oil (Masjuki et al., 2001).

According to review, made by Mat et al. (2018), authors found that under the concentration of 50% of vegetable oil in the diesel fuel the smoke of the engine is reduced. Shah & Ganesh (2016) and Shah et al. (2018) found increased cylinder pressure and reduced smoke of the engine, especially at high engine load, when using filtered vegetable oil as a fuel for CI engine. Rakopoulos et al. (2006) and Hazar & Aydin (2010) found increased smoke density when using not preheated vegetable oil-diesel fuel blends, especially at low engine speed. Sathiyamoorthi & Sankaranarayanan (2017) found increased opacity at low and moderate engine loads and decreased opacity at high engine load.

Particulate matter (PM) produced by combustion engines means serious danger to human health (Kotek et al., 2017). The carbon particles absorb other substances (i.e. hydrocarbons or heavy metals, ect.) on their surface. The harmfulness of the solid particles rapidly increases with their decreasing size and the smallest particles can even enter into the blood stream (Dockery et al., 1992; Mohankumar & Senthilkumar, 2017; Soleimani et al., 2018). The particles with a diameter of 20 nm was found to have the highest deposition efficiency in the alveolar region of the lungs (Warnatz et al., 2006).

The aim of the paper is to experimentally verify the effect of rapeseed and sunflower oil as a fuel admixture on performance parameters and solid particles production of compression ignition engine.

MATERIALS AND METHODS

The measurement was performed using turbocharged compression ignition engine Zetor 1204 placed in the tractor Zetor Forterra 8641 (Fig. 1). The displacement of the engine is 4.156 L, the rated power is 60 kW (53.4 kW on PTO (Power Take Off) according to Deutsche Landwirtschafts-Gesellschaft). The basic parameters of the engine are listed in Table 1. The engine is unmodified and its operating time does not exceed 150 operating hours.

The engine was loaded trough the PTO using mobile dynamometer MAHA ZW 500 (Fig. 1).

Figure 1. The tractor Zetor 8641 with mobile dynamometer MAHA ZW 500.

The dynamometer has maximum torque of 6,800 Nm, maximum braked power of 500 kW and maximum rotation speed of 2,500 rpm. The data from the dynamometer were stored using data acquisition unit, provided by manufacturer, to the hard drive of PC with frequency of 10 Hz. The exhaust gas temperature sensor, fuel temperature sensor and ambient conditions sensors (atmospheric pressure, temperature and humidity) were also connected to the MAHA data acquisition unit. The losses in the gearbox have no effect on the comparative measurement of the influence of fuel on the operational parameters of the engine and therefore they are not taken into consideration.

Table 1. The engine parameters

Manufacturer and type	Zetor 1204
No. and arrangement of cylinders	4, in-line
Air flow	Turbocharged
Rated power	60 kW at 2,200 min^{-1} (53.4 kW on PTO)
Maximum torque	351 Nm (312 Nm on PTO)
Engine displacement volume	4.156 L
Cylinder bore X stroke	105 x 120 mm
Compression ratio	17
Fuel system	Mechanical in-line injection pump
Injection type	Direct injection
Combustion chamber	Bowl-in-piston
Injector noozle	Multihole
Start of injection (SOI)	12° before top dead center
Injection pressure	22 MPa
Valve mechanism	OHV
Valves per cylinder	2

The production of solid particles was measured using the Engine Exhaust Particle Sizer 3090 (EEPS) made by TSI Inc. The particles are evaluated as the count of particles in 1 cm^3. The basic operational parameters of the EEPS particle analyser is shown in Table 2. Before entering the particle analyser the exhaust gas is diluted (dilution factor 99.2667, dilution ratio 0.01007) and cooled down to temperature approx. 23 °C. The pressure of the measured gas is kept at approx. 90 kPa. Data from the particle analyser were stored to the hard drive of PC with the frequency of 1 Hz.

Table 2. The basic parameters of the EEPS

Particle Size Range	5.6–560 nm
Particle Size Resolution	16 channels per decade (32 total)
Electrometer Channels	22
Charger Mode of Operation	Unipolar diffusion charger
Inlet Cyclone 50% Cutpoint	1 µm
Time Resolution	10 size distributions s^{-1}

As a test fuels the diesel fuel blended with vegetable oils were used. As a reference fuel the diesel fuel with no bio-components was used. The following fuel blends were used for the measurement:

- 5% sunflower oil / 95% diesel fuel
- 20% sunflower oil / 80% diesel fuel

- 5% rapeseed oil / 95% diesel fuel
- 20% rapeseed oil / 80% diesel fuel
- 100% diesel fuel according to the regulation EN 590 (Diesel - EN 590) – with no bio-component

The viscosity and density of the tested fuels are shown in Table 3. The values in Table 3 were measured by means of Stabinger Viscometer SVM 3000 made by Anton Paar GmbH (measuring accuracy < 1%, repeatibilty 0.1%).

Table 3. Viscosity and density of the tested fuels

Fuel	Temperature °C	Dynamic Viscosity mPa s	Kinematic Viscosity $mm^2\ s^{-1}$	Density $kg\ m^{-3}$
Diesel fuel	40	1.444	1.801	801.65
	15	2.329	2.843	819.1
20% rapeseed oil	40	2.443	2.984	818.75
	15	4.216	5.042	836.1
5% rapeseed oil	40	1.627	2.022	804.4
	15	2.65	3.224	821.9
20% sunflower oil	40	2.54	3.088	822.45
	15	4.426	5.27	839.85
5% sunflower oil	40	1.647	2.041	806.9
	15	2.726	3.307	824.35

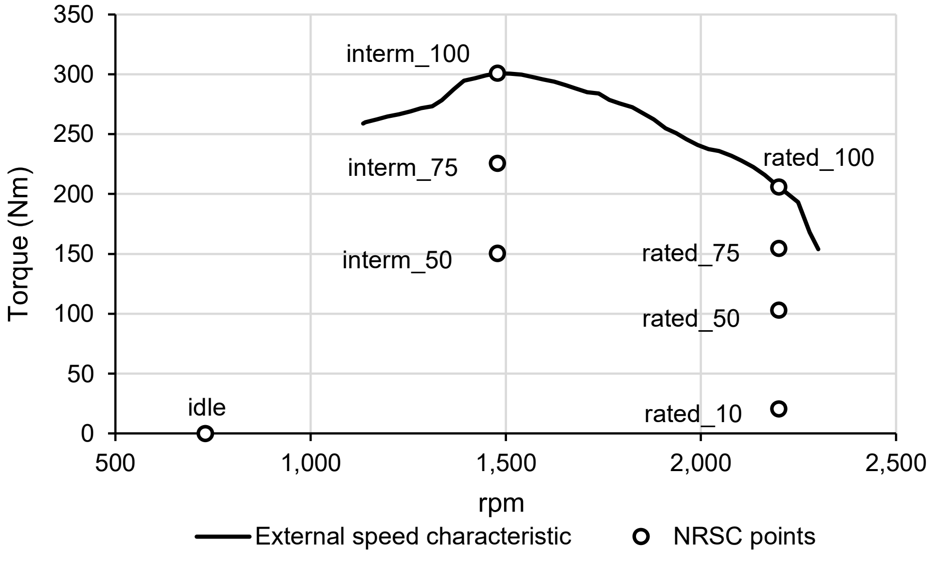

Figure 2. The example of the measurement points for NRSC test for diesel fuel.

The measurement was carried out according to 8-point NRSC (Non-Road Steady cycle) test (ISO 8178-4, type C1). For each tested fuel the torque curve was measured. Then, based on the torque curve, the points for the NRSC cycle was determined for each fuel. Points are defined by rotation speed (idle, at max. torque and rated) and torque (10%, 50%, 75% and 100%). The example of the points for the NRSC test are shown in the Fig. 2. At each measurement point the engine operational parameters are stabilized and then the data are recorded for approx. 80 seconds. The software MS Excel was used for data evaluation.

RESULTS AND DISCUSSION

In the Fig. 3 the torque curves for all tested fuels can be seen. From the figure it is evident that the all tested blends of vegetable oil with diesel fuel caused an increase of the engine torque and power. The higher torque and power could be a result of combinations of different physical properties, such as viscosity and bulk modulus of vegetable oils in comparison with diesel fuel. According to Shah & Ganesh (2016) the different physical properties of fuel could affect injection timing and rate of fuel delivery. Also, the different chemical properties of vegetable oils in comparison with diesel fuel could affect the combustion process and may lead to higher cylinder pressure (Shah et al., 2018). The Table 4 shows the maximal reached values of torque and power for all tested fuels. The increase of torque and power between approx. 2–3% can be seen for all tested blended fuels in comparison with diesel fuel.

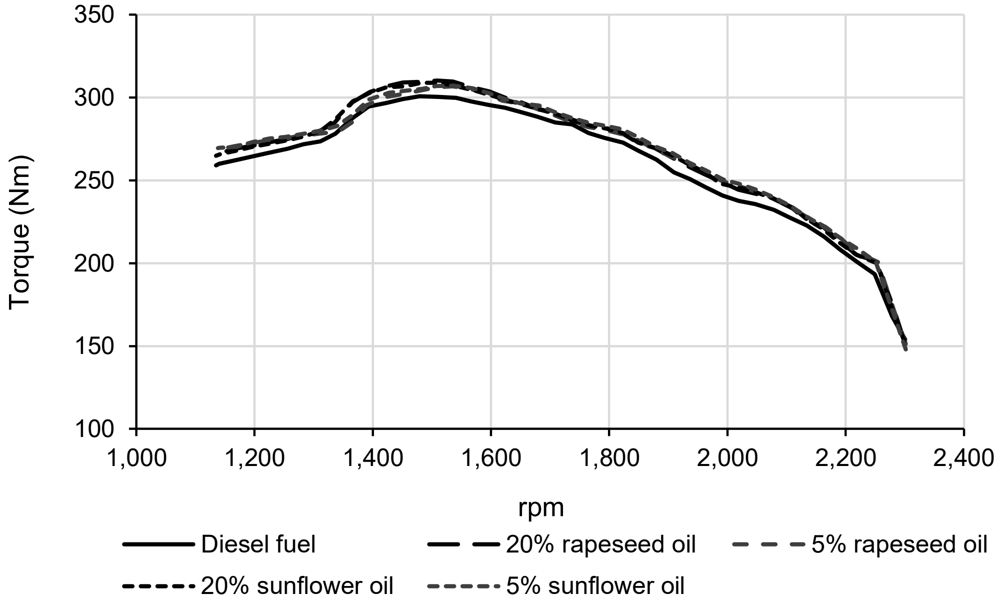

Figure 3. The torque curves, reached with the tested fuels.

Table 4. The maximum reached values of torque and power for all tested fuels

Fuel	Max. torque		Max. power	
	Nm	%	kW	%
Diesel fuel	300.82	100	52.05	100
20% rapeseed oil	310.27	103.14	53.11	102.03
5% rapeseed oil	306.75	101.97	53.07	101.94
20% sunflower oil	308.89	102.68	53.22	102.23
5% sunflower oil	307.11	102.09	53.57	102.92

In the Fig. 4 the results for all 8 points of the NRSC test for diesel fuel are shown. It can be seen that the engine reaches the highest concentration of solid particles at point rated_10, the size of most produced particles is in range of 45.3–69.8 nm.

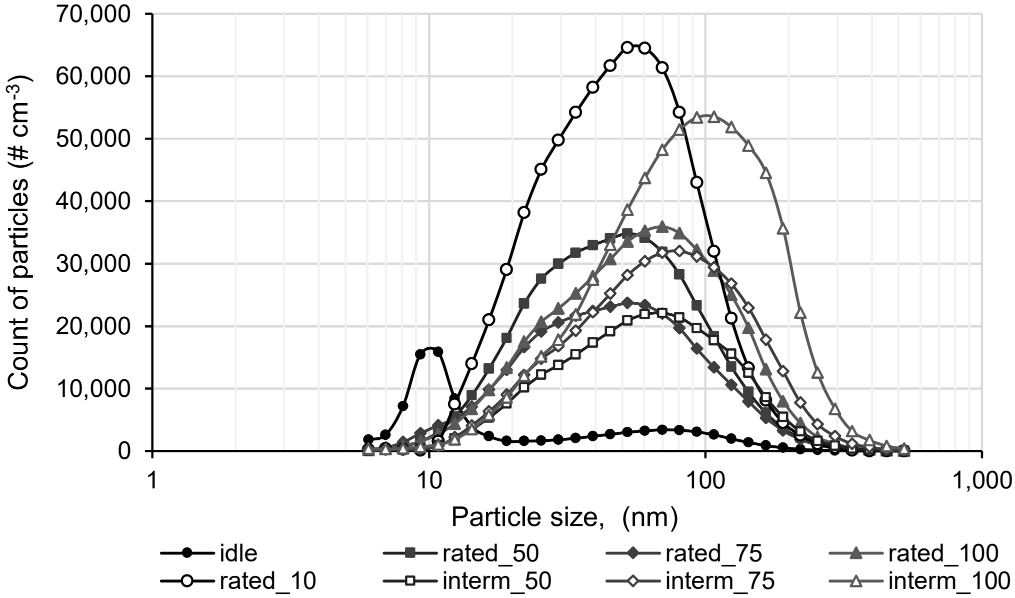

Figure 4. The results of particles analysis for diesel fuel.

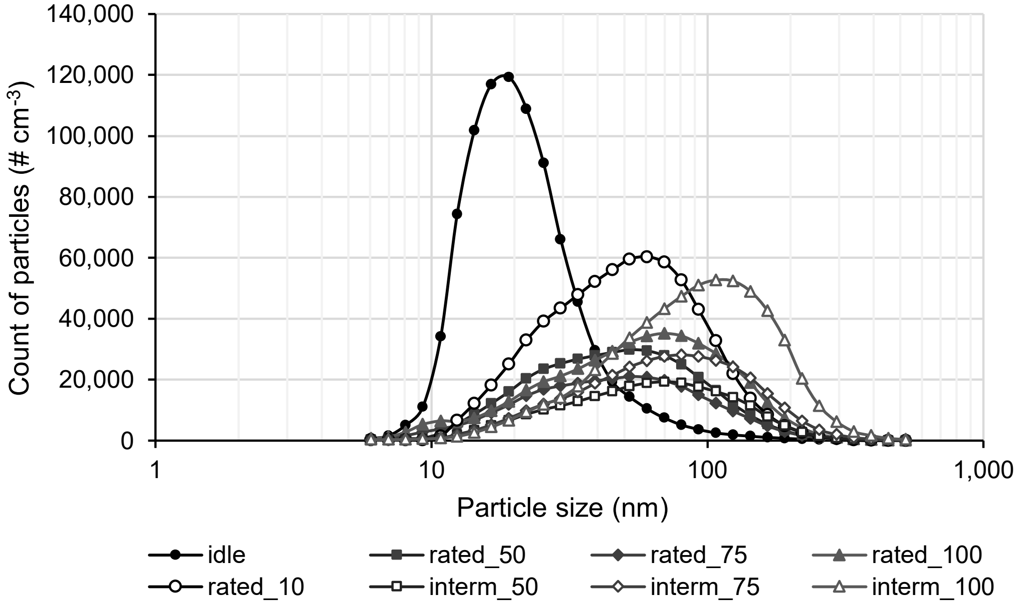

Figure 5. The results of particles analysis for the fuel containing 20% of rapeseed oil.

In the Fig. 5 the results of particle analysis for the blended fuel with 20% rapeseed oil are shown. It can be seen that the main difference in comparison with the diesel fuel is reached at idle. In comparison with the diesel fuel the substantial increase can be seen in production of the very small particles. Rakopoulos et al. (2006) and Hazar & Aydin (2010) also found the increase smoke density for vegetable oil-diesel fuel blends, particularly at low engine speed. This may be caused by the combination of higher viscosity of the fuel, containing 20% of rapeseed oil, and therefore worse atomization of the fuel, and worse evaporation, caused by worse evaporation ability of the vegetable oils in comparison with diesel fuel. Since in idle the substantial part of the combustion is premixed combustion, the effect of worse evaporation is increased. Also, it can be seen that in the case of fuel with 20% of rapeseed oil the maximum concentration of produced particles while engine idle is in the range of approx. 14.3–22.1 nm, while in case of diesel fuel it is in the range of 9.31–10.8 nm. However, the maximum concentration of produced particles at idle is more than 6.5 times higher in the case of fuel with 20% of rapeseed oil in comparison with diesel fuel. In other measurement points the engine, running on blended fuel with 20% of rapeseed oil, produced lower concentrations of particles with slightly bigger sizes in comparison with the diesel fuel.

In the Fig. 6 the results of particle analysis for the fuel blended with 5% of rapeseed oil are shown. From the figure it is evident that at idle the amount of produced solid particles in the small sizes is substantially lower than in the case of fuel with 20% of rapeseed oil, but their size is also lower. The most particles, produced while idle, has size of 10.8 nm. In other points of the NRSC test the engine tends to produce less amount of solid particles in comparison with the diesel fuel or fuel, containing 20% of rapeseed oil. The sizes of particles are approximately the same as in the case of fuel with 20% of rapeseed oil (except idle).

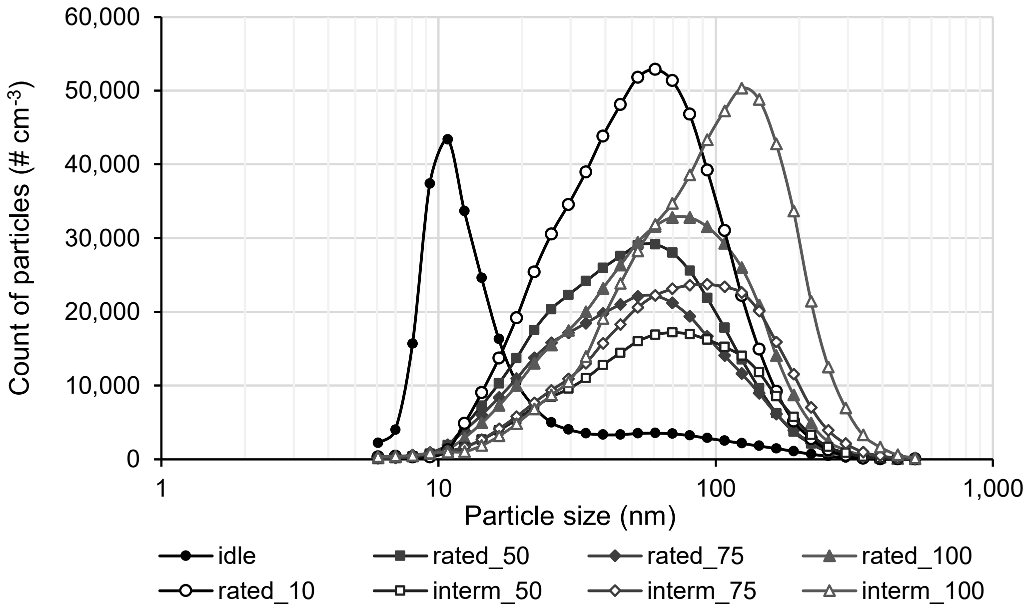

Figure 6. The results of particles analysis for fuel containing 5% of rapeseed oil.

In the Fig. 7 the results of particle analysis for the fuel blended with 20% of sunflower oil are shown. In comparison with diesel fuel, similar trend as in the case of

20% rapeseed oil can be seen, except of idle, less particles are created and their size is slightly bigger. At idle the substantial increase in production of small solid particles (14.3–19.1 nm) in comparison with diesel fuel occurred, similarly to fuel containing 20% rapeseed oil. In comparison with the results obtained with 20% rapeseed oil the lower number of particles are created while their size remains approximatelly the same.

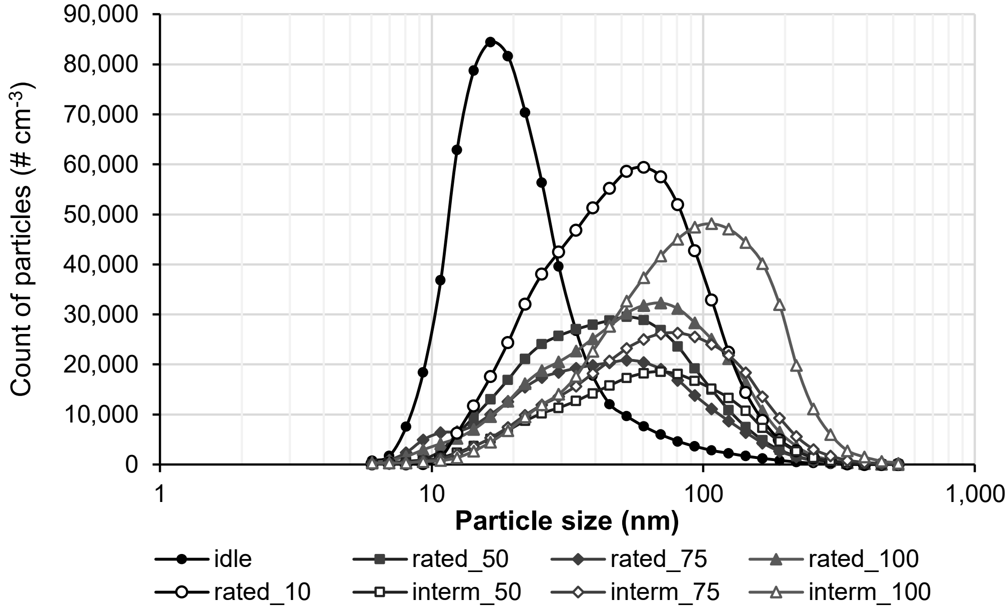

Figure 7. The results of particles analysis for fuel containing 20% of sunflower oil.

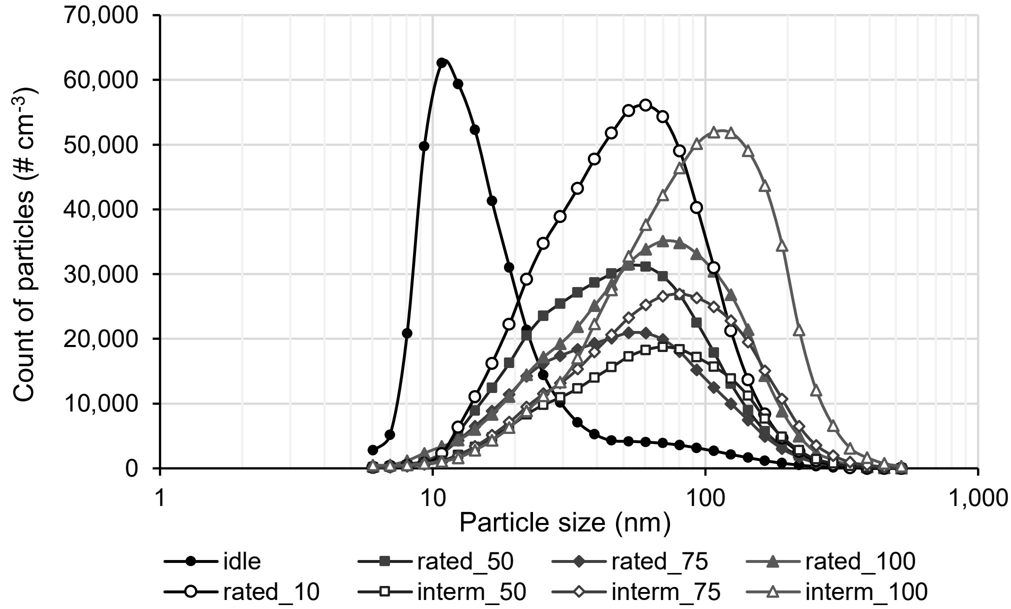

Figure 8. The results of particles analysis for fuel containing 5% of sunflower oil.

In the Fig. 8 the results of particle analysis for the fuel blended with 5% of sunflower oil are shown. In comparison with the rapeseed oil the the results obtained with sunflower oil does not follow the same trend. At points idle, rated_10, rated_75, interm_50 and interm_75 the production of solid particles is lower compared with 20% concentration of sunflower oil. At points rated_50, rated_100 and interm_100 the number of produced solid particles is higher than in case of 20% sunflower oil. From this result it is evident that at high engine load the higher percentage (20%) of sunflower oil reached better results, at moderate engine load the results of 5% and 20% sunflower oil are comparable and at low engine loads the 5% sunflower oil reached better results. At idle the decrease of amount of produced small solid particles can be seen, but compared to the fuel blend with 5% rapeseed oil the amount of particles is still approx. by 44.3% higher (at size 10.8 nm).

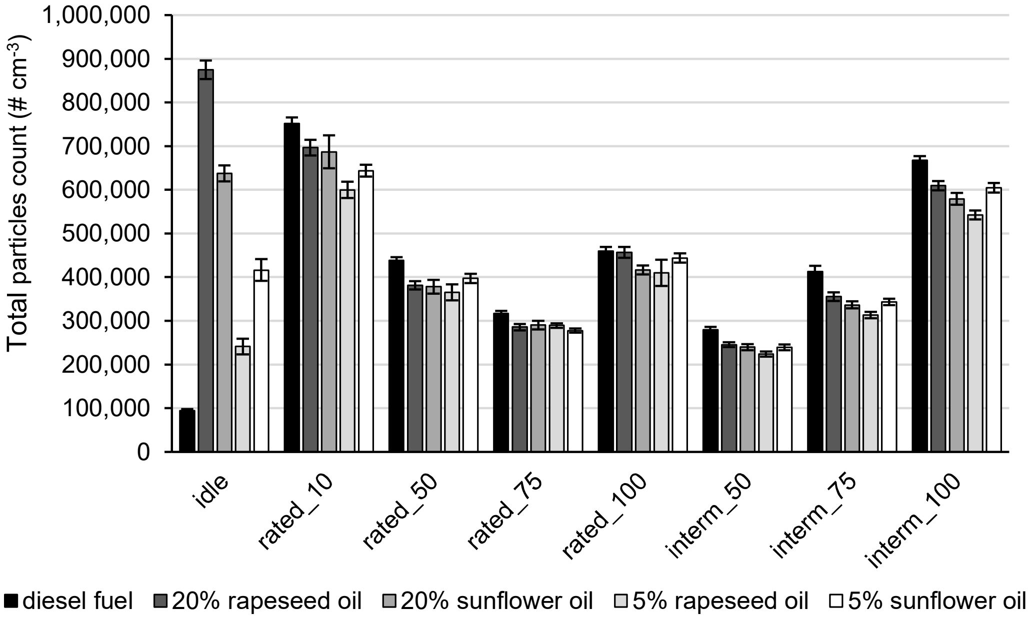

Figure 9. The total particles count for all tested fuels (error bars represents the standard deviation of the measured data).

In the Fig. 9 the total count of produced solid particles for all tested fuels is shown. Except of idle the highest amount of solid particles was produced by engine operating on diesel fuel. However, the vegetable oils caused substantial increase of production of solid particles at idle where the smallest particles that can be detected by the measuring device are produced. In the Table 5 the comparison of total count of produced particles in percentage is shown. From the table it is evident that, except of idle, all tested blended fuels achieved better results than diesel fuel. According to Shah & Ganesh (2016) this can be explained by higher oxygen content and lower carbon content in vegetable oils in comparison with diesel fuel.

It may be also noted that from the blended fuels the best result was achieved with fuel, containing 5% rapeseed oil (except rated_75). In comparison with diesel fuel the fuel with 5% of rapeseed oil decreased the total solid particles count by 8.7–24.2% (except idle).

Table 5. Comparison of total particles count in 1 cm^3 for all tested fuels

Measurement point	Diesel fuel	20% rapeseed oil	20% sunflower oil	5% rapeseed oil	5% sunflower oil
-	%	%	%	%	%
idle	100	922.08	671.91	254.02	438.61
rated_10	100	92.66	91.37	79.75	85.59
rated_50	100	87.00	86.20	83.30	90.59
rated_75	100	90.16	91.69	91.35	87.70
rated_100	100	99.33	90.63	89.14	96.56
interm_50	100	87.57	85.56	79.90	85.31
interm_75	100	86.06	81.44	75.79	83.11
interm_100	100	91.37	86.90	81.36	90.65

CONCLUSIONS

From the results of measurement the following conclusions were made:

- The addition of both rapeseed and sunflower oil in concentration of 5% and 20% resulted in increased torque and power of the engine. The torque and power increase was between approx. 2–3%.
- When operating on 5% and 20% sunflower or rapeseed oil the engine tends to create slightly bigger particles in comparison with diesel fuel.
- Addition of rapeseed and sunflower oil in concentration of 5 and 20% resulted in decreased production of solid particles by approx. 0.7–24.2% in 7 from 8 measured points.
- The substantial increase of production of solid particles occurred when engine idling. The cause may be the combination of low temperature, insufficient atomization of the fuel with high viscosity and poor evaporation of the vegetable oil before premixed combustion. The increase of injection pressure may help to solve the problem.
- From tested fuel blends the fuel with 5% rapeseed oil and 95% diesel fuel showed the best result in terms of solid particles production.

From the obtained results it can be claimed that in comparison with diesel fuel the addition of rapeseed or sunflower oil in the concentration up to 20% into the diesel fuel decreases the production of particulate matter in most of tested engine mods despite increased viscosity of the blended fuels. The substantially increased production of very small particles while engine idle could be possibly solved by increased injection pressure, addition of butanol (Atmanli et al., 2015; Hönig et al., 2015; Pexa et al. 2016) or preheating of the fuel in order to improve atomization of the fuel.

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