INFLUENCE OF DIESEL – BUTANOL FUEL BLENDS ON PRODUCTION OF SOLID PARTICLES BY CI ENGINE

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Abstract
The paper deals with the size distribution and count of solid particles produced by agricultural CI engine, operated on fuel blends of butanol and fossil diesel fuel in comparison with 100% diesel fuel. 5 and 20% concentrations of n-butanol in diesel fuel were used as a test fuels. For measurement the turbocharged engine Zetor 1204, mounted in the tractor Zetor Forterra 8641, was used. The particles were evaluated by means of EEPS (engine exhaust particle sizer) made by TSI, Inc. according to their size and count. The engine was measured in stabilized conditions at rated speed of 2200 min^{-1} under 50%, 75% and 100% engine load. The results showed lower total count of produced solid particles when using both of blended fuels in comparison with diesel fuel. Also, the size of the particles tended to decrease with increasing proportion of n-butanol in the fuel blend.

Key words: *solid particles; CI engine; n-butanol; blended fuel; tractor.*

INTRODUCTION
Simple alcohols such as butanol, ethanol or methanol as well as vegetable oils are considered as promising potential biofuels. They can be used as additives or blended fuels in CI engines. It is proven that diesel blended with alcohols decrease NO_x and PM emissions *(Killol et al., 2019)*. Compared to ethanol and methanol, n-butanol has some different qualities, such as higher energy content, enabling it to be directly blended and the advantage of not being strongly hygroscopic. Properties of butanol are also considerably closer to diesel fuel *(Rezgui & Guemini, 2016)*. Mentioning the fuel delivery methods, burning butanol in diesel engines can be realized through direct injection of neat butanol or blends with diesel *(Abdullah et al., 2019)*. Butanol has a lower auto-ignition temperature and thus it can be burned easier *(Li et al., 2019)*. Engine oil dilution is one of the problems which occurs in the diesel engine. During the cold start of the engine, the unburnt non-vaporized feedstock is condensed on the cylinder liner wall and is blown through the piston ring and dilutes with the lubricating oil in the crankcase. Fuel dilution also reduces the viscosity of engine oil, which makes lubrication oil film weaker and leads to crankcase bearing wear *(Choi, Lee & Park, 2016)*. Although there are many studies about butanol and vegetable oil blended in biofuel, but there is still limited information of combustion characteristics over a range of blends of n-butanol and diesel including vegetable oils *(Lampe et al., 2018)*. The aim of this paper was to compare the size distribution and count of solid particles produced by agricultural CI engine, operated on butanol-diesel fuel blends and 100% diesel fuel.

MATERIALS AND METHODS
During this experiment three different fuels were compared. Firstly, 100% diesel fuel (D100) with no added bio-component was used as a reference for experiment. Consequently, two fuel blends were used as tested fuels: 95% diesel fuel blended with 5% of n-butanol (BUT5) and 80% diesel fuel blended with 20% of n-butanol (BUT20). Density, kinematic viscosity and calorific value of the tested fuels are shown in Tab. 1. The values of density and kinematic viscosity were measured by means of Stabinger Viscometer SVM 3000 made by Anton Paar GmbH (measuring accuracy < 1%, repeatability 0.1%).
The values of calorific value of the fuels were reached by means of isoperibol calorimeter LECO AC600 (measuring range 23.1–57.5 MJ kg^{-1} for a 0.35 g sample, accuracy 0.1% RSD) according to ČSN DIN 51900-1 and ČSN DIN 51900-2.

Tab. 1 Fuel properties ([1]data obtained from *EN 590*, [2]data obtained from *Imtenan et al. 2015* and *Atmanli et al. 2015*, [3]data obtained from *Rakopoulos et al. 2010*)

	Calorific value $MJ.kg^{-1}$	Kinematic viscosity $mm^2.s^{-1}$	Density at 15°C	Cetane number
D100	43.151	1.8013	819.133	50[1]
BUT5	42.438	1.7125	817.971	-
BUT20	41.076	1.7052	817.083	-
BUT100	33.101	2.226	815.270	17[3]-25[2]

The measurements were carried out using compression ignition engine Zetor 1204 with turbocharger, mounted in the tractor Zetor Forterra 8641. The given specifications of the engine are shown in Tab. 2. The engine is in factory setup and it has never been used in outdoor conditions, only for laboratory testing. Its overall operating time does not exceed 160 operating hour.

Tab. 2 Parameters of the tractor engine

Manufacturer and type	Zetor 1204
Cylinders	4, in-line
Air flow	Turbocharged
Rated power	60 kW at 2200 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

A data acquisition unit, provided by manufacturer, was used to store the data from the dynamometer to the computer with the frequency of 10 Hz. The tractor was loaded via PTO (Power Take Off) using mobile dynamometer MAHA ZW 500. Specification of the dynamometer can be seen in Tab. 3.

Tab. 3. Basic dynamometer specification

Manufacturer and type	MAHA ZW 500
Max. power	500 kW
Max. torque	6,600 Nm
Max. speed	2,500 min^{-1}
Torque inaccuracy	< 1% over the full speed range

TSI Engine Exhaust Particle Sizer 3090 (EEPS) was used for measuring of the production of solid particles. The basic operational parameters of the EEPS particle analyser is shown in Tab. 4. This device evaluates particles as the count of particles in volume 1 cm^3.

Tab. 4. EEPS 3090 specification

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}

The exhaust gas is diluted before entering the particle analyser (dilution ratio 0.01007, dilution factor 99.2667) and then 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.
The measurements were carried out at rated engine speed 2200 min^{-1} in stabilized conditions. The loads of the engine were calculated from maximum torque at 2200 rpm for each fuel. The load of the engine was maintained at 50%, 75% and 100%. At each measurement point the monitored parameters were stabilized. After stabilization the monitored parameters were recorded for approx. 80 s. The mechanical losses in gearbox have no real influence on comparative measurement and therefore they were not taken into account. The MS Excel was used for evaluation of the measured data.

RESULTS AND DISCUSSION

In Fig. 1 the particle size distribution for all tested fuels at 50% engine load is shown. It is evident that the concentration of produced solid particles was lower when using both of blended fuels in comparison with D100, which can be explained by higher oxygen content of the blended fuels.
Also, the blended fuels showed lower mean size of the produced solid particles compared with D100. With increasing proportion of n-butanol in the fuel blend the mean size of solid particles decreased (D100 – 55.53 nm, BUT5 – 52.98 nm, BUT20 – 49.47 nm). This can be explained by lower viscosity of the fuel blends in comparison with D100 and therefore better atomization. Also, higher volatility of n-butanol in the fuel blends could contribute to lower size of particles, especially during premixed combustion phase.

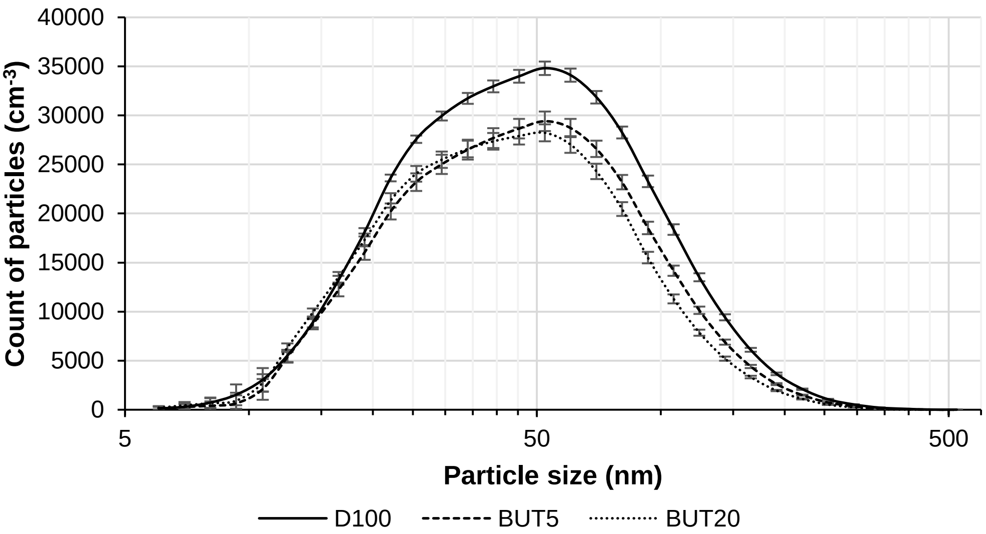

Fig. 1 Particle size distribution for all tested fuels at 50% engine load

In Fig. 2 the particle size distribution for all tested fuels at 75% engine load is shown. From the figure it can be seen that both of the blended fuels reached lower concentration of solid particles in practically all sizes in comparison with D100. However, the difference between BUT5 and BUT20 is more significant than in the case of 50% engine load. The higher particles concentration, reached with BUT20 in comparison with BUT5 may be caused by the properties of n-butanol in the fuel blend, especially by its

lower cetane number. Lower cetane number of BUT20 fuel cause later ignition of the fuel and therefore affects the combustion process, while BUT5 have its properties closer to D100.
Similarly to 50% engine load, the mean size of the particles decreased with increasing proportion of n-butanol in the blend (D100 – 56.28 nm, BUT5 – 54.83 nm, BUT20 – 50.64 nm).
Fig. 3 shows the particle size distribution for all tested fuels at 100% engine load. It is evident that both of blended fuels decreased production of solid particles in comparison with D100, similarly to other measured engine loads. However, similarly to 75% engine load, higher production of solid particles in the size range of approx. 10–70 nm was reached using BUT20 in comparison with BUT5.
Using all tested fuels the mean size of the produced solid particles increased with increasing engine load. Due to lower viscosity of the fuel blends, the mean size of produced solid particles was lower when using both of the blended fuels in comparison with D100 (D100 – 68.7 nm, BUT5 – 65.88 nm, BUT20 – 57.25 nm).
Similar results, concerning lower production of solid particles and size when using n-butanol–diesel fuel blends, were also found by *Jindra et al. (2016)*, especially at higher engine load. Other authors *(Zhang & Balasubramanian, 2014; Geng et al., 2019)* also found lower concentration and lower mean diameter of produced solid particles after addition of n-butanol into biodiesel–diesel fuel blends.

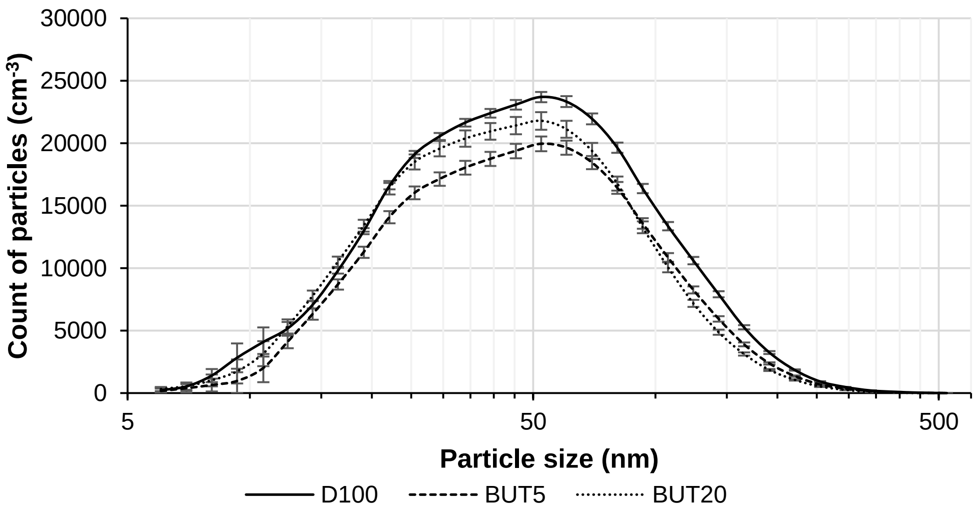

Fig. 2 Particle size distribution for all tested fuels at 75% engine load

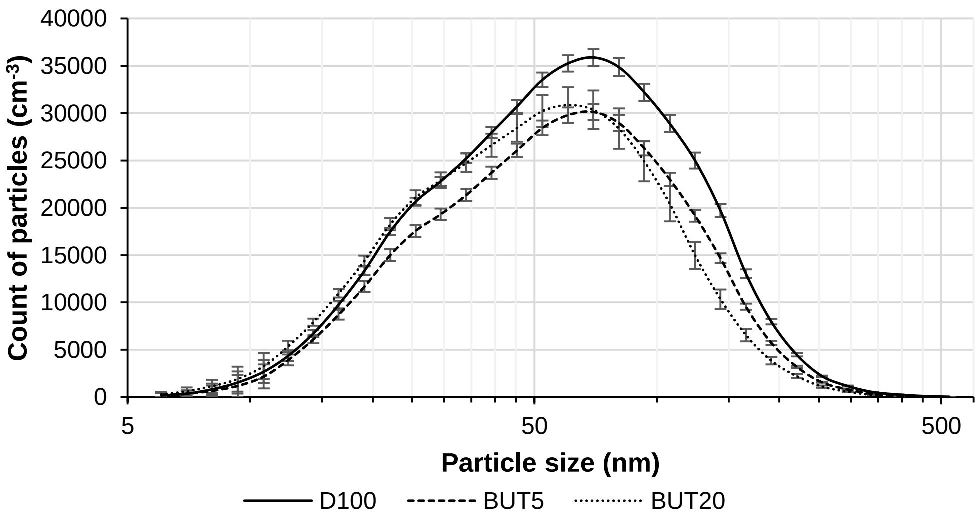

Fig. 3 Particle size distribution for all tested fuels at 100% engine load

In Fig. 4 the total particles count, reached with all tested fuels at all measured engine loads can be seen. It is evident that the lowest concentration of solid particles was reached at 75% engine load. Also at all measured engine loads the both of blended fuels decreased the total solid particles production. Using BUT5 the decrease was approx. 16.9% at 50% engine load, 17.8% at 75% engine load and 17.3% at 100% engine load. When running on BUT20 fuel blend the decrease of solid particles production was approx. 19.8% at 50% engine load, 10.7% at 75% engine load and 14.5% at 100% engine load. The statistically significant difference was found between all tested fuels in all measured engine loads using the analysis of variance (ANOVA). Tab. 5 shows ANOVA, complemented with Tukey HSD post-hoc test for all tested fuels at all measured engine loads.

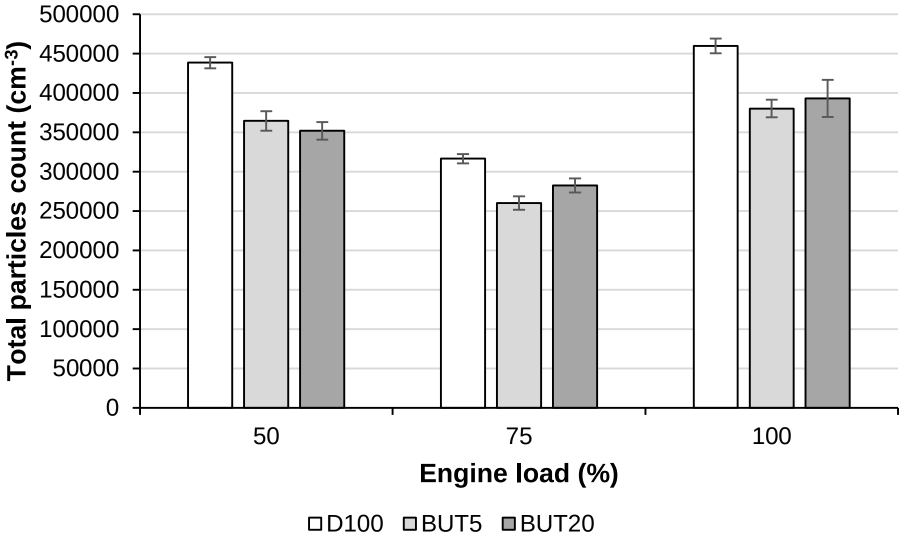

Fig. 4 Total particles count for all tested fuels at all measured engine loads

Tab. 5 ANOVA with Tukey HSD post-hoc test for total particles count at full engine load (α = 0.05)

ANOVA				
	Sum of squares	Degrees of freedom	Variance	F
Between groups	2.14E+11	2	1.07E+11	448.4478
Within groups	4.09E+10	171	2.39E+08	
Total	2.55E+11	173		

Tukey HSD Post-hoc Test

D100 vs BUT5: Diff=-79544.6571, 95%CI=-86154.4040 to -72934.9102, p=0.0000

D100 vs BUT20: Diff=-66771.9298, 95%CI=-73817.7415 to -59726.1181, p=0.0000

BUT5 vs BUT20: Diff=12772.7273, 95%CI=5957.5440 to 19587.9106, p=0.0000

CONCLUSIONS

From the results of the performed measurement the following conclusions were made:

- The count of produced solid particles decreased at practically all sizes for both of the fuel blends except fuel BUT20 at size range of approx. 10–70 nm.
- Statistically significant difference in total solid particles production was found between all tested variants at all measured engine loads while at higher engine load (75% and 100%) BUT5 fuel showed the lowest solid particles production.
- The mean size of the particles decreased with increasing proportion of n-butanol in the fuel blend.

The paper is focused on comparison of solid particles production of turbocharged CI engine operating on n-butanol–diesel fuel blends and 100% diesel fuel. From reached results it can be stated that addition of n-butanol into diesel fuel have positive effect on decrease of the number of produced solid particles by CI engine.

ACKNOWLEDGMENT
The contribution was created with the grant support CULS IGA – 2019:31190/1312/3101 - The effect of biofuels on the process of combustion and characteristics of running the internal combustion engine.

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