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EFFECT OF BIOBUTANOL-SUNFLOWER OIL-DIESEL FUEL BLENDS ON COMBUSTION CHARACTERISTICS OF COMPRESSION IGNITION ENGINE

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Based on many regulations the biofuels are widely used in combustion engines. The operational parameters, such as performance parameters or emission production, are often monitored. The essence of changes to these operational parameters is related to the effect of biofuels on the course of cylinder pressure inside the combustion chamber. The contribution deals with the effect of biobutanol-sunflower oil-diesel fuel blends on the performance parameters, the behaviour of the cylinder pressure of the compression ignition engine during combustion, and exhaust gas temperature. Biobutanol-sunflower oil-diesel fuel blends in ratios of 10–20–70% and 20–20–60% were used as test fuels, with diesel fuel used as a reference. Turbocharged four-cylinder in-line CI engine Zetor 1204 installed in the tractor Zetor Forterra 8642 was used for measurement. Based on the results, it can be stated that with higher amount of butanol in the fuel mixture, the maximum value of cylinder pressure decreases, especially at a high engine load.

Keywords: biofuels; combustion engine; cylinder pressure; vegetable oil; performance parameters; heat release rate

There are different approaches to the effort to reduce the environmental impact of transportation and agricultural machinery operation (Tulík et al., 2014; Beloev et al., 2017; Tkáč et al., 2017). The utilization of variety of biofuels as an alternative to the fossil fuels in combustion engines contributes to this effort. Biofuels based on vegetable oils or alcohols are most commonly used for CI engines (Babu et al., 2017; Birzietis et al., 2017; How et al., 2018; Mat et al., 2018).

In comparison with diesel fuel, 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 and Nguyen, 2011; Esteban et al., 2012). It can be used as an admixture to diesel fuel or other fuel blends (Franco and Nguyen, 2011). According to Masjuki et al. (2001) and Mat et al. (2018), a fuel blend containing 30% vegetable oil and 70% diesel fuel can be burned in CI engine without need for modification of the engine or preheating the fuel.

According to Shah and Ganesh (2016) and Shah et al. (2018), vegetable oil increases the cylinder pressure due to longer ID as a result of high level of unsaturated fatty acids and advanced injection.

In order to reduce the viscosity of the fuel without preheating, alcohol-based fuel admixtures can be used. Butanol is a second generation biofuel and can be used as a fuel admixture for CI engines in order to decrease the viscosity of the fuel blends containing biodiesel or vegetable oil (Atmanli et al., 2015; Babu et al., 2017).

In comparison with ethanol, butanol has a lower auto-ignition temperature, higher calorific value and is less evaporative. It also has a higher cetane number and better lubricating ability than ethanol and methanol. It is also less corrosive and better miscible with vegetable oils, diesel and FAME (Hönig et al., 2015a, 2015b; Müller et al., 2015).

The addition of butanol to neat vegetable oil or biodiesel reduces the cetane number and viscosity of the blends, which leads to better mixing and higher premixed combustion (Rakopoulos, 2013). The addition of butanol to vegetable oil-diesel fuel blends causes decrease of peak cylinder pressure, especially in high engine load, due to retarded start of combustion, caused by low cetane number of butanol, and large heat of evaporation of butanol (Sharon et al., 2013; Imtenan et al., 2015; Babu et al., 2017).

The purpose of this contribution is to experimentally verify the influence of n-butanol-vegetable oil-diesel fuel blends on performance parameters, cylinder pressure profile, and HRR profile during combustion.

Material and methods

The measurement was performed using turbocharged CI engine Zetor 1204 installed in the tractor Zetor Forterra 8641 (Fig. 1). The engine parameters are listed in Table 1. The engine is unmodified and its operating time does not exceed 150 operating hours.

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Table 1 Parameters of used CI engine Zetor 1204

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 nozzle	Multihole
Start of injection (SOI)	-12 °ATDC
Injection pressure	22 MPa
Valve mechanism	OHV
Valves per cylinder	2

ATDC – after top dead centre

The engine was loaded through the PTO using mobile dynamometer MAHA ZW 500 (Fig. 1). The dynamometer has maximum torque of 6,800 Nm (torque measurement inaccuracy <1%), 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, at a 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 are not taken into consideration.

The position of the crankshaft was measured using incremental sensor SICK DKS with 3 channels (2 with 360 impulses per revolution – used for measurement, and 1 with 1 impulse per revolution – used as a trigger).

The cylinder pressure was measured by means of piezoelectric pressure sensor Optrand (model C322-GPA, measuring range 0–20.7 MPa, accuracy 1%), mounted instead of the glowplug. For each impulse from the incremental sensor, the value of cylinder pressure was recorded (measurement resolution = 1 °CA).

Fig. 1 Dynamometer MAHA ZW 500, connected to the tractor Zetor Forterra 8641

The mixtures of sunflower oil, diesel fuel and n-butanol were selected as test fuels. Diesel fuel with no bio-additives was used as a reference. Basic properties of the tested fuels are shown in Table 2. The values of density and viscosity were measured by means of Stabinger Viscometer SVM 3000 manufactured by Anton Paar GmbH (viscosity range 0.2–30,000 $mm^2\ s^{-1}$, density range 0.6–3 g cm^{-3}, measuring accuracy <1%, repeatability 0.1%). The calorific values of the tested fuels were measured 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. Following fuel blends were used for the measurement:

- 100% diesel fuel with no bio-additives (D100),
- 70% diesel fuel / 20% sunflower oil / 10% n-butanol (SO20BUT10),
- 60% diesel fuel / 20% sunflower oil / 20% n-butanol (SO20BUT20).

The monitored engine modes were selected from the 8-point NRSC test cycle, which is standardized for the used engine type by ISO 8178-4 (type C1). The points for the NRSC test are established according to the external rotation speed characteristics of the engine and defined by engine load and speed. In order to analyse the effect of n-butanol-sunflower oil-diesel fuel blends on the cylinder pressure and performance parameters, the following measurement points were selected:

- idle – measurement point no. 1,
- maximum torque at corresponding speed – measurement point no. 2,

Table 2 Basic properties of the utilised fuels

Fuel	Density at 15 °C (kg m^{-3})	Calorific value (MJ kg^{-1})	Viscosity at 40 °C ($mm^2\ s^{-1}$)	Cetane number
D100	819.13	43.15	1.798	50**
N-butanol	815.27	33.1	2.266	17***
Sunflower oil	924.05	37.01	31.148	35.8*
SO20BUT10	837.1	40.72	2.849	-
SO20BUT20	836.35	39.74	2.834	-

Source: *Cisek and Szlachta, 2001; **EN 590, 2013; ***Atmanli et al., 2015

– maximum power at rated speed – measurement point no. 3.

Each measurement point was stabilized and the data recorded for approx. 60 seconds, in order to eliminate cycle to cycle variations. Software MS Excel was used for data processing. ANOVA was used to evaluate the peak cylinder pressure values at all measured points.

HRR, as the most effective way to obtain information about the combustion process, was calculated according to Eq. (1). The calculation is based on the first law of thermodynamics and does not take into account the heat transfer trough the cylinder walls. Mixture preparation, fuel vaporization, non-equilibrium and non-homogenous conditions do not have to be taken into account (Ozsezen et al., 2008; Imtenan et al., 2015). In order to eliminate noise effects, the Savitzky-Golay smoothing filter was used on the recorded pressure data:

$$\frac{dQ}{d\theta}=\frac{\gamma}{\gamma-1}p\frac{dV}{d\theta}+\frac{1}{\gamma-1}V\frac{dp}{d\theta} \qquad (1)$$

where:

$dQ/d\theta$ – heat release rate, J/°CA
V – instantaneous cylinder volume, m^3
p – instantaneous cylinder pressure, Pa
θ – crankshaft angle, deg
γ – ratio of specific heats at constant pressure and volume (considered constant at 1.35 (Heywood, 1988; Imtenan et al., 2015))

The ID is the period between SOI and SOC. In the case of the utilised engine, the SOI is kept constant at -12 °ATDC. SOC can be determined by various methods (Aldhaidhawi et al., 2017). According to some sources (Heywood, 1988; Aldhaidhawi et al., 2017), change of slope in the HRR profile defines the SOC, other sources (e.g. Imtenan et al., 2015) state that SOC occurs once the HRR becomes positive. The moment when HRR becomes positive was used for SOC determination in the observations performed.

Results and discussion

In Fig. 2, the external rotation speed characteristics, measured using tested fuels, is shown. It can be seen that the engine reached similar values of torque and power operating on fuel blend SO20BUT10 (the difference of 0.67% falls below the measurement accuracy).

When operating on blend SO20BUT20, the engine reached lower values of maximum torque by approx. 3.8% and power by approx. 2.8% in comparison with the diesel fuel. This decrease of performance parameters is caused above all by low calorific value and cetane number of n-butanol in the mixture. From the external speed characteristics the individual measurement points were established for each tested fuel. The engine speed, torque and power for all tested fuel can be seen in Table 3.

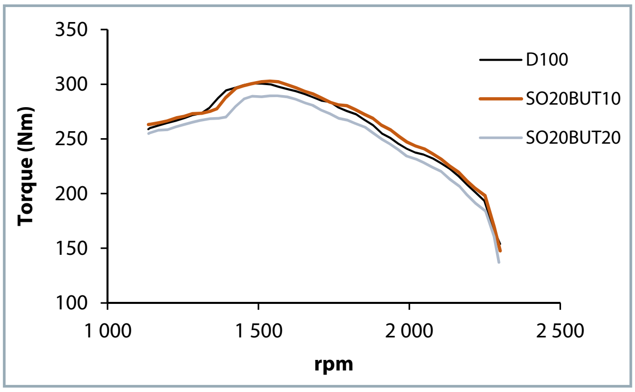

Fig. 2 The external rotation speed characteristics, reached with the tested fuels

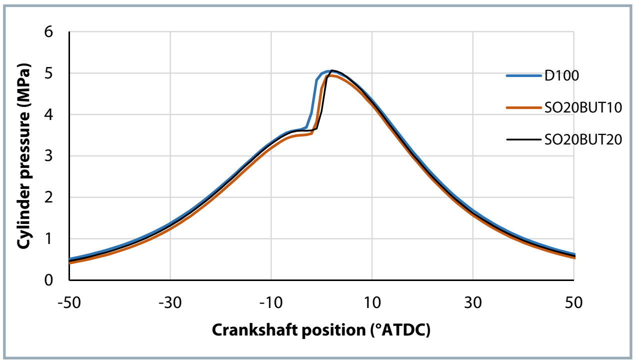

Fig. 3 Cylinder pressure profile in dependence on crankshaft position for all tested fuels at point no. 1

In Figs. 3 and 4, the cylinder pressure profile and the HRR during combustion in dependence on the angle of the crankshaft for measurement point no. 1 are shown. The cylinder pressure offers information about the direct utilization of released heat for useful work. It can be seen that with increasing amount of n-butanol in the fuel blend, the ID is increased as the result of low cetane number of n-butanol. The ID for all tested fuels at all measured points is listed in Table 4. In addition, before the start of combustion the decrease of cylinder pressure in comparison with D100 fuel can be seen. This may be caused by the evaporation of the n-butanol in the fuel blend during ID, since n-butanol

Table 3 Parameters of the measurement points for all tested fuels

Fuel	Point 1			Point 2			Point 3		
	torque	speed	power	torque	speed	power	torque	speed	power
	Nm	rpm	kW	Nm	rpm	kW	Nm	rpm	kW
D100	0	730	0	215.37	2201.77	49.66	297	1537.71	47.83
SO20BUT10	0	730	0	211.66	2202.29	48.81	297.22	1531.83	47.68
SO20BUT20	0	730	0	203.85	2202.63	47.02	283.58	1560.24	46.33

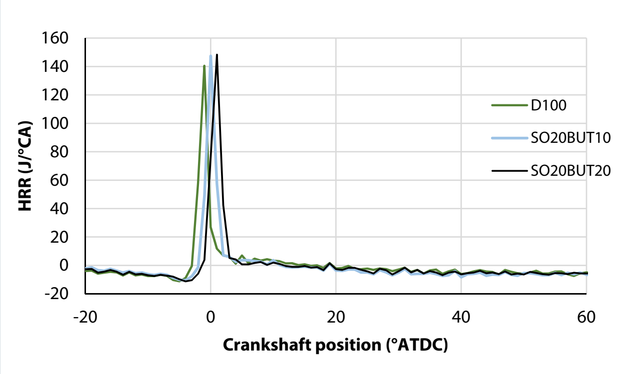

Fig. 4 HRR profile in dependence on crankshaft position for all tested fuels at point no. 1

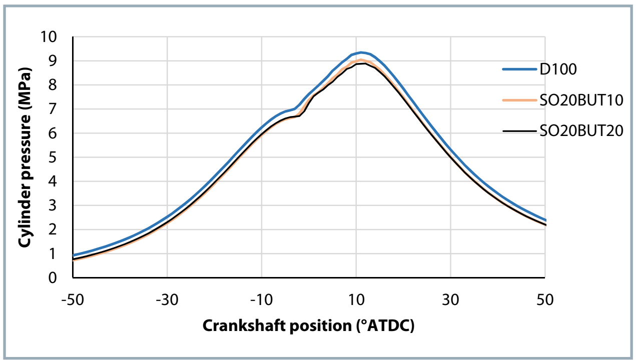

Fig. 5 Cylinder pressure profile in dependence on crankshaft position for all tested fuels at point no. 2

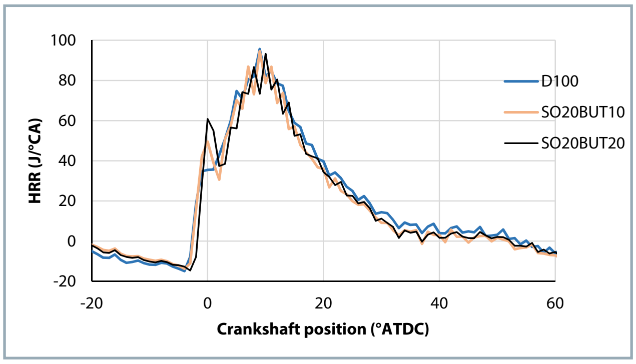

Fig. 6 HRR profile in dependence on crankshaft position for all tested fuels at point no. 2

has higher heat of evaporation than diesel fuel (Imtenan et al., 2015; Xiao et al., 2017).

From Fig. 4 it is evident that at measurement point no. 1 (idle), the main part of heat is released during premixed part of the combustion, with the highest peak of HRR is reached with fuel SO20BUT20. This also reflects the highest peak cylinder pressure, which is also reached with fuel SO20BUT20. The ID is prolonged for both blended fuels, with the longest ID achieved with the fuel SO20BUT20 (Table 4). The increased premixed combustion and ID when using n-butanol or other alcohol-based fuel blends in CI engine was reported previously (Rakopoulos, 2013; Tutak et al., 2015; Geng et al., 2017).

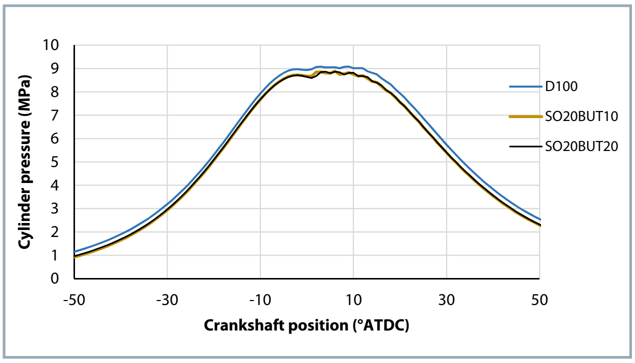

Fig. 7 Cylinder pressure profile in dependence on crankshaft position for all tested fuels at point no. 3

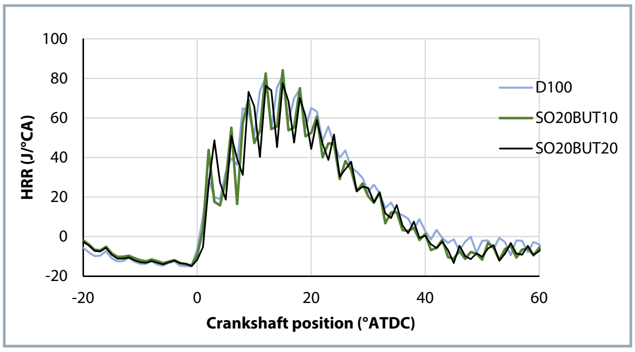

Fig. 8 HRR profile in dependence on crankshaft position for all tested fuels at point no. 3

In Figs. 5 and 6 the cylinder pressure profile and the HRR profile in dependence on the crankshaft position for measurement point no. 2 can be seen. From the cylinder pressure profile, it is evident that for both blended fuels the cylinder pressure is decreased in comparison with D100. From the HRR profile, it can be seen that, in comparison with D100, the premixed part of the combustion is increased for both blended fuels, with the premixed combustion being strongest for fuel SO20BUT20. The ID is increased for fuel SO20BUT20 due to low cetane number of n-butanol. Additionally, it can be seen that the EOC appears later for D100 fuel.

In Figs. 7 and 8, the cylinder pressure profile and the HRR profile in dependence on crankshaft position for measurement point no. 3 can be seen. Similarly to the point no. 2, the decrease of cylinder pressure can be seen for both blended fuels in comparison with D100. Similar results at high engine loads, caused by low calorific value of n-butanol and its large heat of evaporation, were reached by other authors (Imtenan et al., 2015; Babu et al., 2017). On the contrary, Sharon et al. (2013) found increased cylinder pressure after addition of n-butanol to diesel-biodiesel blends due to increased ID. Additionally, the decrease of cylinder pressure before SOC, caused by high latent heat of evaporation of n-butanol, for both blended fuels can be seen. From the viewpoint of HRR profile, the similar trend can be seen at other measurement points: the premixed combustion is increased and ID is prolonged, however, the prolongation is not as significant as in the case of other two measurement points due to higher rotation speed (Table 4). The end of combustion occurred earlier for blended fuels in

Table 4 Ignition delay for all measured fuels

Fuel	Point 1			Point 2			Point 3		
	D100	SO20 BUT10	SO20 BUT20	D100	SO20 BUT10	SO20 BUT20	D100	SO20 BUT10	SO20 BUT20
ID (°CA)	9.01	10.03	10.6	9.3	9.41	10.22	12.4	12.73	13.17

Table 5 Analysis of variance of peak cylinder pressure, complemented with Tukey HSD post-hoc test for point no. 1

ANOVA				
α = 0.05	Sum of squares	Degrees of freedom	Variance	F
Between groups	5.0003	2	2.5001	294.8
Within groups	12.6703	1494	0.0085	
Total	17.6706	1496		
Tukey HSD Post-hoc Test				
D100 vs SO20BUT10: Dif = -0.1058, 95% CI = -0.1198 to -0.0918, p = 0.0000				
D100 vs SO20BUT20: Diff = 0.0233, 95% CI = 0.0092 to 0.0373, p = 0.0003				
SO20BUT10 vs SO20BUT20: Diff = 0.1290, 95% CI = 0.1159 to 0.1422, p = 0.0000				

ANOVA – analysis of variance

comparison with D100, since the higher amount of fuel is burned during premixed combustion phase.

In Table 5, the results of ANOVA of peak cylinder pressure, complemented with Tukey HSD post-hoc test, for measurement point no. 1 is shown. The statistically significant difference was found between all tested fuels at all measurement points. Other authors have previously found increased peak cylinder pressure when using sunflower oil (Shah and Ganesh, 2016) or other vegetable oils or its blends with diesel fuel (Sathiyamoorthi and Sankaranarayanan, 2017; Shah et al., 2018). From the obtained results, it is evident that n-butanol in the fuel blends has stronger effect on cylinder pressure than sunflower oil, since the pressure is decreased at points 2 and 3.

Conclusions

The article is focused on comparison of performance parameters, cylinder pressure profile and HRR profile of CI engine operating on n-butanol-sunflower oil-diesel fuel blends and diesel fuel. From the results of the measurements, the following conclusions were made:

- The similar performance parameters of engine operating on SO20BUT10 were reached during measurement (the difference is under the measurement accuracy). During operation on SO20BUT20 fuel blend, the performance parameters were decreased by approx. 3%. The cause for this is primarily the low calorific value of n-butanol.
- Peak cylinder pressure was decreased for blended fuels as a result of their lower calorific value and large heat of evaporation of n-butanol.
- The n-butanol in the fuel blend increased the ID in all measured points as a result of its low cetane number. With increasing amount of n-butanol in the fuel blend, the ID is increased.
- Heat released during premixed combustion phase was increased for blended fuels in comparison with D100, while, with increasing proportion of n-butanol in the fuel blend, the premixed combustion was stronger.
- Diffusion combustion phase was practically unchanged when using fuel blends in comparison with D100.
- At the late combustion phase, the EOC occurs earlier for fuel blends than for D100.

It was found that the main problem of using n-butanol-sunflower oil-diesel fuel blends in CI engine is the low cetane number of n-butanol and its large heat of evaporation in comparison with the diesel fuel. The combustion process could be improved by earlier start of injection or by adding cetane number improvers like 2-ethylhexylnitrate (Atmanli et al., 2015).

Abbreviations

CA – crankshaft angle, CI – compression ignition, DLG – Deutsche Landwirtschafts-Gesellschaft, EOC – end of combustion, FAME – fatty acid methyl ester, HRR – heat release rate, ID – ignition delay, NRSC – non-road steady cycle, PTO – power take off, RSD – relative standard deviation, SOC – start of combustion, SOI – start of injection

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