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Influence of butanol and FAME blends on operational characteristics of compression ignition engine

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Abstract. The issue of the use of alternative fuels in diesel engines is discussed in this paper. The purpose is to reduce the dependence of EU Member States on fuels of petroleum origin. One of the possibilities is the use of butanol produced from organic products. The use of pure butanol in diesel engines is not possible. However, it may be used as an additive for fuels of petroleum origin or adding to oil for improving the operating conditions of the engine. Successively 10, 30 and 50% n-butanol was used as an additive. Turbocharged combustion engine of the tractor Zetor 8641 Foretrra was used to the test. This engine was burdened using a dynamometer to the PTO. Performance parameters and fuel consumption of the engine were monitored during measurements. Performance parameters of the engine decreases and fuel consumption increases due to the properties of butanol. Cleansing properties of butanol which restrict carbonization on functional surfaces of the engine seems advantageous.

Key words: Biofuels, power, fuel consumption, combustion engine, butanol, FAME.

INTRODUCTION

According to European Directive 2009/28/EC the target in the field of renewable sources is substitution of 10% energy in transport by energy derived from renewable sources by 2020. In order to reach this target the liquid biofuels are used.

For diesel engines the fatty acid methyl esters are most frequently used. Fatty acid methyl ester (FAME) has a lower mass calorific value, higher density and higher viscosity than diesel (Kučera & Rousek, 2008; Hromádko et al., 2011; Pexa & Mařík, 2014). FAME can be made from vegetable oil and animal fat (Sirviö et al., 2014). The inferior storage and oxidative stability are the main disadvantages of FAME. Another disadvantage of FAME is a high feedstock cost, especially when the vegetable oil is used as a raw material. Using of animal fat, which is currently a waste product, can override this disadvantage (Barrios et al., 2014). Studies show that the internal combustion engine operating on rapeseed methyl ester (RME) achieves lower power by approx. 5–10%, higher fuel consumption and a lower average thermal efficiency by approx. 3.5%, but a higher thermal efficiency by 3% at maximum load (Hromádko et al. 2011; Soo-Young, 2011; Pexa & Kubín, 2012; Imran et al., 2013; Pexa et al., 2013).

Other biofuels are fuels based on alcohol. Ethanol is the most used alcohol fuel. Ethanol as a fuel for diesel engines is not frequently used due to low cetane number, decreased flash point, worsened lubricity, low energy content, worse miscibility and higher volatility (Kleinová et al., 2011). Butanol is an alternative to the use of ethanol. Butanol has a lower auto-ignition temperature, it is less evaporative and releases more energy per unit of mass. It also has a higher cetane number, higher energy content and better lubricating ability than ethanol and methanol. It is also less corrosive and better miscible with vegetable oils, diesel and FAME. When mixed with diesel or FAME slightly increases specific fuel consumption and lowers the temperature of the exhaust gases because of its lower calorific value in comparison with diesel (Bhattacharya et al., 2003; Doğan, 2011; Yilmaz et al., 2014).

It was found, that butanol/FAME/diesel blends decreases the cetane number and viscosity of the fuel with increasing share of butanol (Wadumesthrige et al., 2010), ,furthermore, these blends increases the specific fuel consumption and reduces harmful emissions (CO, PM, soot) (Sukjit et al., 2012; Zhang & Balasubramanian, 2014). FAME/Butanol blends can lower the combustion temperature and thereby lower the emissions of NO_X and soot (Soloiu et al., 2013).

The purpose of the measurements was to determine the effect of butanol mixed with FAME based on animal fats, to a torque, power and specific fuel consumption of supercharged diesel engine. Due to the characteristics of butanol such as the lower heating value and a lower cetane number the decrease of performance parameters and increase of specific fuel consumption with increasing share of butanol can be expected.

MATERIALS AND METHODS

The measurement was done using the tractor engine Zetor 1204 prefilled by means of turbocharger and placed in the tractor Zetor Forterra 8641. It is in-line 4 cylinder engine, its volume is 4.156 and rated power 60 kW (it is 53.4 kW on PTO according to the measurement made by Deutsche Landwirtschafts-Gesellschaft), the maximum torque is 351 Nm, the nominal specific fuel consumption is 253 g kWh^{-1} and the rated speed is 2200 min^{-1}. The fuel is delivered to the engine by means of mechanical in-line injection pump, injecting is done by one injection with pressure 22 MPa, 12° before top dead center. The operating time of the mentioned engine does not exceed 100 operating hours.

The engine was loaded by the dynamometer AW NEB 400 connected to PTO, torque was recorded by the torque sensor MANNER Mfi 2,500 Nm_2000U min^{-1} with accuracy 0.25%. The torque values recorded by the sensor placed on PTO are converted to the engine torque by means of appropriate gear ratio (3.543). The losses in the gearbox have no effect on the comparative measuring of the influence of fuel on the external speed characteristics of the engine and therefore they are not taken into consideration. The fuel consumption was recorded by means of the flowmeter AIC VERITAS 4004 with measurement error 1%. Data were saved on the hard disk of the measuring computer (netbook), with the use of A/D converter LabJack U6 with frequency 2 Hz, in the form of text file. The programmes MS Excel and Mathcad were used for data evaluation.

As a test fuels 10, 30 and 50%$_{vol}$. mixtures of n-butanol (BUT) and FAME from animal fat were selected. Basic features of both components are shown in Table 1. The density and viscosity of mixed fuels are in Table 2. As a reference fuel the conventional diesel was used (ČSN EN 590).

Table 1. Basic parameters of the fuel components

Fuel	Density (kg m^{-3})	Heating value (MJ kg^{-1})	Viscosity at 40 °C (mm^2 s^{-1})	Cetane number
n-Butanol	810[1] (at 28 °C)	32.5[1]	2.63[3] (3.64 at 20 °C)[2]	17.0[3]
FAME	877[2] (at 17 °C)	39.86[2]	5.07[2]	58.8[2]

[1](Honig et al., 2014), [2](Mařík et al., 2014), [3](Öner & Altun, 2009), [4](Lujaji et al., 2011)

Table 2. Basic parameters of the measured fuels

Fuel	Density at 15 °C (kg m^{-3})	Viscosity at 40 °C (mm^2 s^{-1})
10% BUT 90% FAME	869.9	3.88
30% BUT 70% FAME	860.9	3.28
50% BUT 50% FAME	844.5	2.68

The external speed characteristics of the engine were measured for tested fuels at full engine load. Based on these characteristics, the measuring points were determined for the complete characteristic of specific fuel consumption. The points were selected to cover the whole range of engine load and speed. Subsequently, these points were connected by the polynomial function of the third degree with two unknown variables, using the method of least square error using Mathcad. Then the measuring points of the eight-point NRSC (Non-Road Steady Cycle) test were determined according to ISO 8178-4 (type C1). The test was used for measuring the specific fuel consumption. Specific fuel consumption for the whole NRSC test was calculated according to the equation (1). In every predetermined measurement point the measured parameters were stabilized.

$$m_{NRSC} = \frac{\sum_{i=1}^{8}\left(M_{Pi} \cdot WF_i\right)}{\sum_{i=1}^{8}\left(P_{PTO,i} \cdot WF_i\right)} \qquad (1)$$

where: m_{NRSC} – Specific fuel consumption for whole NRSC test (g kWh^{-1}); $M_{P,i}$ – hourly fuel consumption (g h^{-1}); WF_i – weight factor (–); $P_{PTO,i}$ – power on the PTO (kW).

RESULTS AND DISCUSSION

External rotation speed characteristic measured for mixed fuels was created (Fig. 1). It can be seen that the highest performance parameters from mixed fuels achieves fuel containing only 10% butanol which caused 16.4% decrease of maximum torque and 18.6% decrease of maximum engine power compared to the diesel. Higher concentrations of butanol (30 and 50%) cause a noticeable decrease in maximum power and torque compared with 10% BUT. Loss of maximum engine power for 30% BUT is approximately 8.6% and for 50% BUT approximately 10% compared with 10% BUT. The decrease of the maximum engine torque was 11.1% for 30% BUT and 13.6% for 50% BUT compared with 10% BUT.

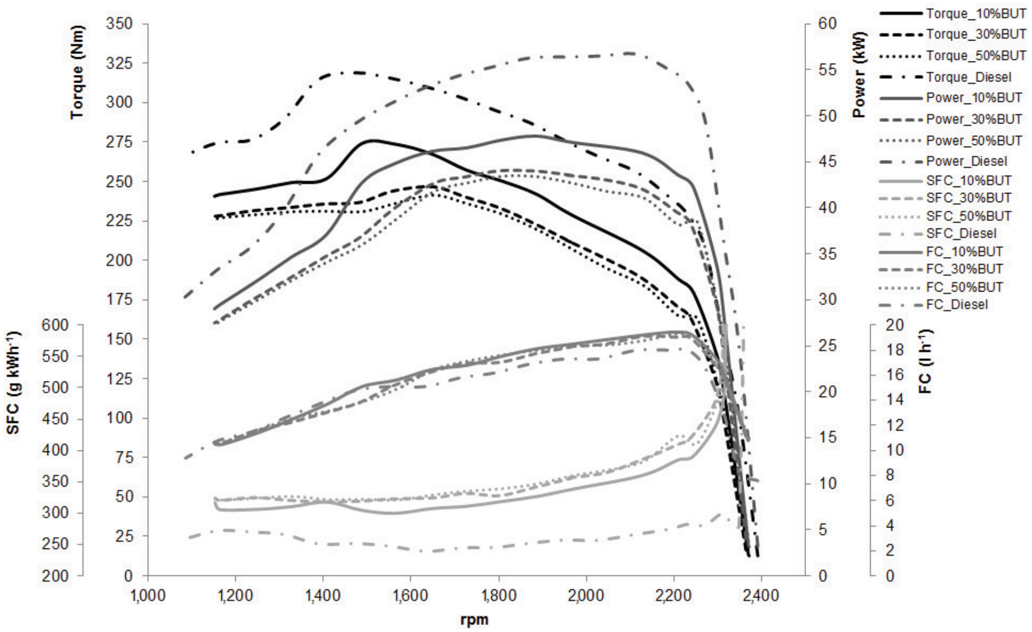

Figure 1. The external rotation speed characteristics for measured fuels (SFC – specific fuel consumption, FC – fuel consumption).

The large decrease of the maximum torque and the engine power (Table 3) is caused on the one hand by the low calorific value of n-butanol an FAME and on the other hand by the low cetane number of butanol (Table 1).

Complete characteristics of specific fuel consumption for each variant were created (Figs 2, 3, 4). From the complete and external rotation speed characteristics the minimums of the specific fuel consumption were determined. Compared with the diesel an 25.3% increase of min. specific fuel consumption can be seen for fuel containing 10% BUT. In comparison with 10% BUT the minimum specific fuel consumption for 30% BUT was higher by approx. 5.7% and for 50% BUT by approx. 6.5% (Table 3).

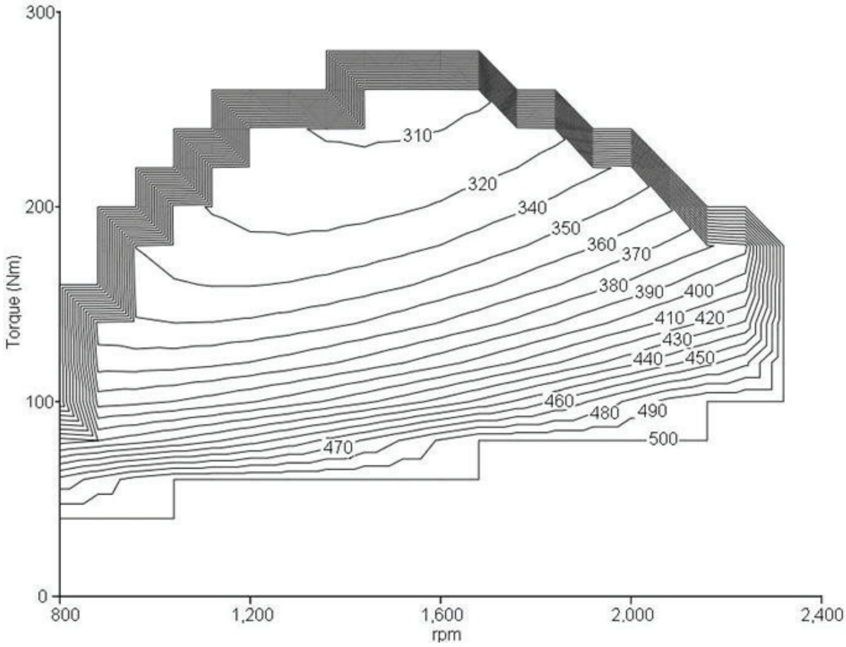

Figure 2. Full characteristic of specific fuel consumption for 10% BUT (g kWh^{-1}).

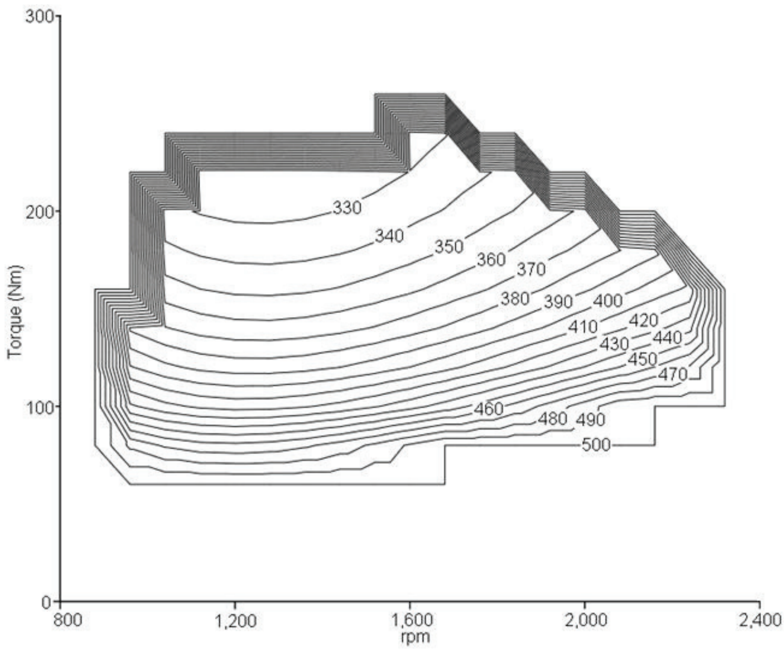

Figure 3. Full characteristic of specific fuel consumption for 30% BUT (g kWh^{-1}).

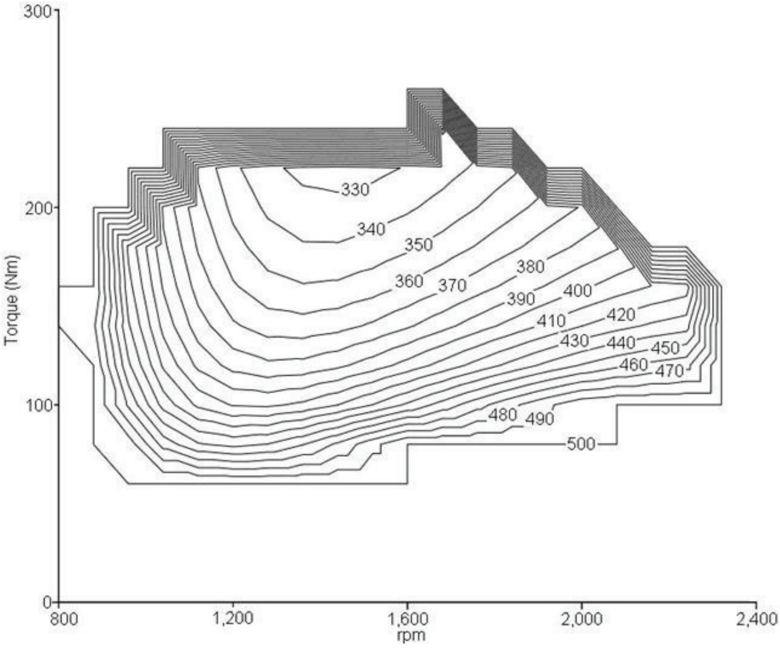

Figure 4. Full characteristic of specific fuel consumption for 50% BUT (g kWh^{-1}).

Table 3. Results of the measurement (SFC – specific fuel consumption)

Fuel	Max. Torque (Nm) rpm	Max. Power (kW) rpm	Min. SFC (g kWh^{-1}) rpm	Rated Torque (Nm)	Rated Power (kW)	Rated SFC (g kWh^{-1})	Torque backup (%)
10% BUT	274.1	47.8	300.04	190.4	43.9	382.2	44
90% FAME	1,488	1,886	1564				
30% BUT	246.67	44.03	318.4	172.5	39.7	407	43
70% FAME	1,652	1,801	1405				
50% BUT	241.4	43.4	321.2	167.4	38.6	418.1	44.2
50% FAME	1,652	1811	1,568				
Diesel	319	56.7	239.4	237.4	54.7	276.6	34.4
	1,474	2,115	1,633				

From the results of the external rotation speed characteristics and from the complete characteristics it is evident that the increase of specific fuel consumption for all variants of mixed fuels is higher with increasing speed and share of butanol in comparison with diesel. At rated speed the specific fuel consumption for 10% BUT increased by 38.2% compared with the diesel. For 30% BUT there is an increase of specific fuel consumption in rated speed by 6.1% and for 50% BUT by 8.5% in comparison with 10% BUT. Further, the results of the specific fuel consumption measured using the NRSC test were evaluated (Table 4). The table shows that the NRSC specific fuel consumption is higher for 10% BUT by 26.8% compared with diesel. For 30% BUT the NRSC specific fuel consumption is higher by 5% and for 50% BUT approximately by 8% compared with 10% BUT. It can be seen that with increasing concentration of butanol the specific fuel consumption increases.

Table 4. Results of the NRSC test for specific fuel consumption

Fuel	SFC (g kWh^{-1})	SFC (%)
10% BUT 90% FAME	424.3	100
30% BUT 70% FAME	445.7	105
50% BUT 50% FAME	457.9	107.9
Diesel	310.5	73.2

CONCLUSIONS

From the obtained results it can be seen that a high share of butanol in the fuel significantly reduces torque and engine performance. From the mixed fuels the highest difference is between 10% and 30% concentrations of butanol. The decrease of performance for 30% and 50% BUT is primarily due to lower heating value and cetane number of butanol compared with FAME, which confirms the assumptions mentioned in the introduction. Also it was proven the increase of specific fuel consumption at higher concentrations of butanol (30 and 50%) compared with 10% BUT at all measured cases (external rotation speed characteristic, complete characteristics and NRSC), especially at higher speeds, which is primarily caused by low cetane number of butanol. In this case the assumptions mentioned in the introduction were also confirmed.

During measurement the butanol showed its good miscibility with FAME by significantly reducing the viscosity of the fuel. The reduce of viscosity is most significant at 10% BUT, as shown in Tables 1 and 2. Further advantages of butanol can be seen in its ability to dissolve the deposits in the fuel system and thereby prolonging its durability.

In conclusion it can be recommended the use of butanol as an additive to FAME up to concentration of 10% BUT, primarily to reduce the viscosity of the fuel. At higher concentrations the other properties of butanol such as low cetane number and calorific value have already quite negatively impacts.

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