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Comparison of exhaust emissions and fuel consumption of small combustion engine of portable generator operated on petrol and biobutanol

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Abstract. The paper is focused on the comparison of exhaust emissions and fuel consumption of small internal combustion engines operated on petrol and biobutanol. In case of this research, small engines are represented by combustion engine of portable power generator with nominal power of 4.8 kW equipped with carburettor for fuel mixture preparation. Exhaust emissions and fuel consumption were measured while gradual loading of the combustion engine. BrainBee emission analyser, Bruker FTIR spectrometer and EEPS particle analyser was used for the measurement. The mass fuel consumption was monitored using laboratory scale Vibra. The initial hypothesis expected that exhaust emissions and fuel consumption will be higher in case of use of nonstandard fuels. From the viewpoint of particles count can be stated, that their productions are at very low level for both kinds of used fuels. Production of carbon monoxide and hydrocarbons is higher than in case of usual automobile engine due to simple engine control system and absence of additional emission control device (catalytic converter). The fuel consumption increased while using n-butanol as a result of its lower calorific value.

Key words: biobutanol, petrol, emission, fuel consumption.

INTRODUCTION

In the Europe the biofuels are widely used as an alternative to fossil fuels. They reduce the increase of greenhouse gasses in the atmosphere, dependency on fossil fuel products and their import, furthermore the biofuels are usually produced from local crops and thus supports the local production (Demirbas, 2009). In the Europe the aim is to achieve a 10% share of energy from renewable sources in transport in 2020 according to EU directive 2009/28/EC.

For SI engines the alcohol based biofuels are most commonly used. The ethanol is mostly used as an alcohol based biofuel for spark ignition engines. However, the ethanol has many disadvantages such as its affinity to the water, aggression to the most of rubber and plastic sealing elements, low calorific value etc. (Čedík et al., 2014a, 2014b).

The alternative to ethanol as alcohol-based biofuel could be butanol. Butanol is the second generation biofuel and it is mainly studied as an admixture in diesel or biodiesel fuels in compression ignition engines (Rakopoulos et al., 2010; Altun et al., 2011; Tüccar et al., 2014; Yilmaz et al., 2014). Butanol can be produced by fermentation or in petrochemical way, so its production is very similar as ethanol (Ezeji et al., 2003). Properties of butanol are closer to fossil fuels. However use of pure butanol in spark ignition engines mainly requires the modification of the air-fuel mixing ratio, due to lower stoichiometric ratio of butanol, similar as when using ethanol. Butanol has several advantages over ethanol, such as a lower ignition temperature and higher calorific value. Butanol is more mixable with hydrocarbon fuels and its stoichiometric ratio is closer to gasoline than when using ethanol. This ratio allows the use of higher concentrations of butanol in gasoline without engine modification. Butanol is also less corrosive due to lower affinity for water. (Durre, 2007; Qureshi et al., 2008; Shapovalov & Ashkinazi, 2008; Andersen et al., 2010; Harvey & Meylemans, 2011; Swana et al., 2011; Serras-Pereira et al., 2013). Gasoline fuel blended with butanol was studied in the range of 3–100% vol. butanol (Rice et al., 1991; Alasfour, 1997; Yacoub et al., 1998; Gautam & Martin, 2000a; Gautam & Martin, 2000b; Dagaut & Togbé 2008; Dagaut & Togbé, 2009; Wallne et al., 2009; Williams et al., 2009; Yang et al., 2009; Dernotte et al., 2010; Wigg et al., 2011; Gu et al., 2012; Feng et al., 2013; Elfasakhany, 2014). The results show that addition of butanol reduces fuel emissions of CO, HC, CO_2, but NO_X emissions are increased depending on concentration and conditions, as compared with gasoline. Increase the emissions of CO and HC and NOx emissions are reduced at concentrations greater than 60% butanol. Due to lower heating value than gasoline the specific fuel consumption is higher and the torque and power are lower compared with gasoline. Better combustion efficiency can be achieved due to better anti-detonation characteristics of butanol compared with gasoline and higher oxygen content. Some sources indicate the increase torque and reduce energy consumption at 35% concentration of butanol in gasoline (Feng et al., 2013). Other sources state that the engine power is maintained in proportion to 80% by volume of gasoline and 20% butanol. (Yang et al., 2009). Most of the above studies were carried out on the engines with fuel injection. Sources indicate small ratios to (3, 7, 10 vol.% Butanol) mixture of butanol in gasoline for testing engine carburettor (Elfasakhany, 2014).

The aim of this paper is to compare the emissions production and fuel consumption of the generator when operating at biobutanol and petrol. Monitored will be those emissions components: CO – carbon monoxide, CO_2 – carbon dioxide, NO_X – nitrogen oxides, HC – hydrocarbons, PM – particles and K – smoke).

MATERIALS AND METHODS

Measurements were carried out on mobile generator ProMax 3500A with a rated power of 2.7 kW powered by small Briggs and Stratton engine type Vanguard 6.5HP with a rated power of 4.8 kW. Assembly of small combustion engine and the alternator is suitable for the quick and easy driving of load of the engine. In this case, value of the output current of the alternator is proportional to combustion engine load.

During loading of the combustion engine, there is measured frequency, electrical current and voltage of the output of the generator. Simultaneously with the measurement of electrical parameters is also measured fuel mass flow rate using Vibra AJ 6200 standard precision scale. In order to monitor the operating parameters of the engine during measurements, the oil temperature sensor, fuel temperature sensor and intake air temperature sensor was mounted on the engine. BrainBee emission analyser, Bruker

FTIR spectrometer and EEPS particle analyser was used as testing devices of emissions production (Table 1). All data are stored to the PC memory using RS482 to RS232 interface and for this purposes software application was developed.

Table 1. Parameters of the emission analyzer BrainBee

Component	Resolution	Accuracy
CO	0.01% vol.	0.03% vol. or 5% read value
CO_2	0.1% vol.	0.5% vol. or 5% read value
HC	1 ppm vol.	10 ppm vol. or 5% read value
O_2	0.01% vol.	0.1% vol. or 5% read value
NO	1 ppm	10 ppm vol. or 5% read value
Opacity	0.1%	2%
Temperature	1 °C	2.5 °C

From measured data the mass emissions production was calculated according to Eqs 1 and 2.

$$Q_a = M_p \cdot FA \cdot 3{,}600 \tag{1}$$

where: Q_a – amount of intake air (g h^{-1}); M_p – fuel consumption (g s^{-1}); FA – mixing ratio (kg$_{air}$ kg$_{fuel}^{-1}$)

$$PE_i = \frac{Q_a \cdot E_i}{100} \tag{2}$$

where: $PE_i i$ – amount of produced emission component (g h^{-1}); E_i – mass share of the emission component (%)

The principle of measurement is based on the principle of operation of the internal combustion engine and electric generator. The internal combustion engine operates in the range around 3,000 rpm, corresponding to a frequency of 50 Hz of electric generator output. During loading of the internal combustion engine decreases its speed according to the control part of the engine characteristics. Properly adjusted governor of the engine keeps the engine speed steady regardless of engine load. At the moment when the engine load reaches external speed characteristics, there is a significant change in engine speed and thus the output frequency of the electric generator.

Measurement is aimed at monitoring of fuel consumption and emissions production of internal combustion engine during gradual loading by heating elements connected to electric generator. Emission values are measured in units of volume and based on the intake air quantity converted into units of weight.

Based on engine operation while using pure BA 95 petrol there was selected several measurement points in steps approximately 25% (675 W), 50% (1,350 W), 72% (1,944 W) and 95% (2,565 W) of rated power. Measurement point at full load (100%) is not selected because of possibility of reaching the external speed characteristic of the engine.

Transmission losses and the change in viscosity of oil are not considered. The measurement is performed at an operating temperature, which is dependent on the engine load and ranges from 90 °C to 110 °C of the engine oil temperature.

Used fuels are biobutanol (n-butanol – BUT) and petrol BA95. Especially for this measurement there was fitted BA 95 petrol without any bio-components required by law.

In the Czech Republic ethanol is mainly used as this component. Basic properties of the used fuels are shown in the Table 2.

During the measurement the air–fuel equivalence ratio was monitored (BrainBee – Brettschneider equation). Consequently the air-fuel ratio (AFR) was changed using the choke shutter according to stoichiometric ratio for each fuel. Stoichiometric ratio for pure octane is commonly 14.7:1 and 12:1 for butanol.

Table 2. Basic properties of used fuels (Feng et al., 2015)

Property	n-Butanol	Petrol
Chemical formula	C_4H_9OH	C_4–C_{12}
Molecular weight (g mol^{-1})	74	100–105
Density (kg m^{-3})	810	720–760
Carbon content (%)	65	86
Hydrogen content (%)	13.5	14
Oxygen content (%)	21.5	–
Auto ignition temperature (°C)	343	257
Calorific value (MJ kg^{-1})	33.1	42.9
Latent heat of vaporization (KJ kg^{-1})	716	380–500
Stoichiometric air-fuel ratio	11.2	14.7
Octane number	89	86–94
Boiling temperature (°C)	118	25–275
Adiabatic flame temperature (K)	2,340	2,370

RESULTS AND DISCUSSION

The resulting values of the individual components of the emissions, fuel consumption, engine speed and load are an average of 2 minutes recording with a sampling frequency of 1 Hz. Solid components of the emissions were excluded from the evaluation. Content of solid particles is negligible in case of the SI engine and in terms of measuring devices it is at the border of sensitivity.

Table 3 shows the volume fraction of emission components in exhaust gas of the internal combustion engine. Table 4 gives the calculated values of mass emissions production (with the inclusion of the combustion process, which is dependent on the air-fuel ratio and on the mixture preparation process).

Table 3. Volume fraction of emission components in exhaust gas of observed engine

	Speed rpm	Load W	NO_X ppm	CO %	CO_2 %	HC ppm	Fuel consumption g h^{-1}	Specific fuel consumption g kWh^{-1}
BA 95	3,142	656	88.9	3.82	7.91	104.1	600.1	914.8
	3,121	1,331	175.9	3.92	7.74	120.5	789.4	592.7
	3,101	1,939	363.2	4.09	8.61	129.4	960.3	495.0
	2,989	2,566	660.8	4.68	10.56	137.3	1,162.5	452.9
BUT	3,141	656	155.2	0.77	9.65	44.3	665.8	1,013.9
	3,122	1,330	361.2	1.59	9.35	56.1	883.0	663.8
	3,091	1,941	714.6	2.08	9.82	77.9	1,106.6	570.1
	2,915	2,591	818.3	3.35	11.26	90.9	1,408.8	543.6

According to Table 3 and Table 4 it is obvious that better results was reached by using fuel BA95 in case of emissions of nitrogen oxides, carbon dioxide and fuel consumption. Conversely, by using BUT fuel, there was achieved better emissions of carbon monoxide and hydrocarbons. Interestingly, just production of carbon monoxide and hydrocarbons has decreased by about 50% when using BUT fuel. In contrast, the carbon dioxide emissions and fuel consumption increased by about 10%. Considerable increase in emissions production was achieved in case of nitrogen oxides namely about 60% in comparison with BA95.

Table 4. Calculated values of mass emissions of observed engine

	Speed rpm	Load W	NO_x g h^{-1}	CO g h^{-1}	CO_2 g h^{-1}	HC g h^{-1}	Fuel consumption g h^{-1}	Specific fuel consumption g kWh^{-1}
BA 95	3,142	656	0.797	0.0320	1,040.3	1.37	600.1	914.7
	3,121	1,331	2.076	0.0431	1,340.4	2.09	789.4	592.7
	3,101	1,939	5.215	0.0549	1,813.8	2.73	960.3	495.0
	2,989	2,566	11.485	0.0759	2,690.7	3.51	1,162.5	452.9
BUT	3,141	656	1.261	0.0058	1,150.4	0.53	665.8	1,013.9
	3,122	1,330	3.892	0.0160	1,477.1	0.89	883.0	663.8
	3,091	1,941	9.651	0.0262	1,945.9	1.55	1,106.6	570.1
	2,915	2,591	14.070	0.0537	2,838.3	2.30	1,408.8	543.5

Fig. 1 shows the percentage comparison of the average values of harmful emissions production and fuel consumption when operating at BUT compared to BA95.

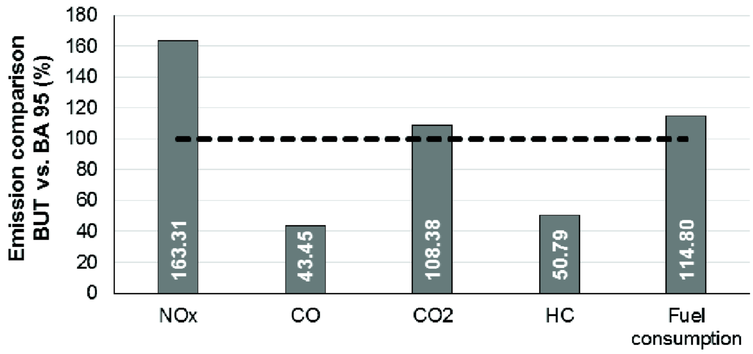

Figure 1. Percentage comparison of emissions and fuel consumption as average for all load modes when operating at BUT where BA95 is represented as 100%.

Fig. 2 shows detailed percentage comparison of emissions of the engine operated at BUT for selected load levels compared with BA95. It is evident, that at low load level when BUT is used emissions of nitrogen oxides, carbon dioxide and fuel consumption are increased in comparison with the BA95 fuel. On the contrary, there is visible decrease in production of carbon monoxide and unburned hydrocarbons. With increasing engine load the production of carbon monoxide, unburnt hydrocarbons and fuel consumption increases. This is probably caused due to the enrichment of the fuel mixture at a higher load. Reduced combustion efficiency at higher loads confirms the declining production of carbon dioxide. With increasing loads, temperature of combustion rises due to a larger amount of mixture delivered into the combustion chamber, which corresponds with higher production of nitrogen oxides. At full load, there is probably insufficient amount of oxygen in the mixture and nitrogen oxides emissions are significantly lower.

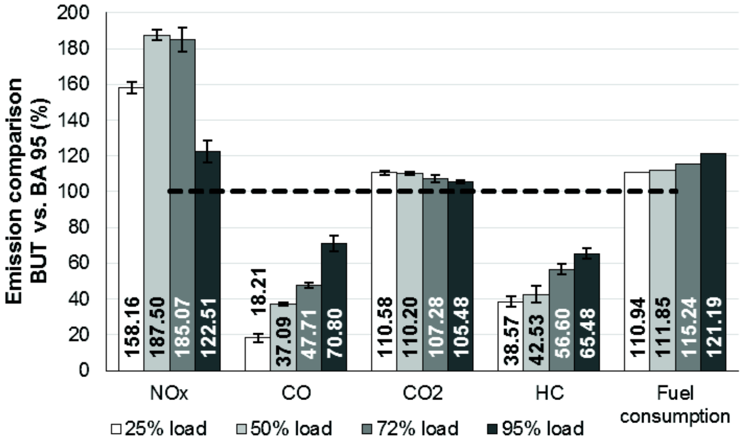

Figure 2. Percentage comparison of harmful emissions and fuel consumption for particular load levels when operating at BUT where BA95 is represented as 100%.

CONCLUSIONS

This paper was aimed on the comparison of exhaust emissions (CO_2, CO, NO_X, HC) of small internal combustion engines fuelled by carburettor, controlled by governor and operated on BA95 petrol and biobutanol. According to results, it can be concluded:

- It was expected that fuel consumption will be higher when operating at butanol due to lower calorific value of butanol. Fuel consumption was about 15% higher in case of butanol.
- When operating at BA95, there was achieved better values of emissions production of NO_X and CO_2 (which is related to fuel consumption). Emissions of NO_X and CO_2 were approximately about 65% and 10% lower than when operating at butanol.
- Conversely, when operating at butanol the better results was achieved in case of CO and HC emissions. Emission decreased significantly about 50%.

Significant improvement in CO and HC emissions during operation at butanol can be associated to a better regulation of the combustion process. When operating at BA95 fuel, the engine operated unattended. When operating at butanol, the air-fuel ratio was monitored and mixture ratio of butanol and air was manually adjusted in order to maintain stoichiometry mixture. Without this intervention the operation of the combustion engine is almost impossible when operating at pure butanol.

The overall engine operation time also influences the production of the exhaust emissions. Therefore, the long-term measurement is needed to confirm the results in real operation conditions.

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