Use of butanol as a fuel for internal combustion engines

V. Hönig[1,*], M. Kotek[2] and J. Mařík[2]

[1]Faculty of Agrobiology, Food and Natural Resources, CULS-Czech University of Life Sciences Prague, Kamycka 129, 16521, Prague 6, Czech Republic; [*]Correspondence: honig@af.czu.cz
[2]Faculty of Engineering, CULS-Czech University of Life Sciences Prague, Kamycka 129, 16521, Prague 6, Czech Republic

Abstract: Currently, the focus of the research and development is devoted to the wider use of fuels of plant origin focused on the possibility of producing a higher quality and use of motor fuel other than bioethanol. BioButanol is thus not only a promising alternative fuel for gasoline, but also a possible replacement for bioethanol as a fuel for internal combustion engines for transportation. Butanol can be produced virtually with the same ingredients as bioethanol, but in terms of fuel property, it is a preferable alternative to bioethanol. The efficient technology for its production by direct fermentation of simple sugars by fermentation, enzymatic hydrolysis or modified polysaccharides is currently the subject of intensive research work. The paper presents fuel properties of butanol and simultaneously compared with the properties of gasoline and bioethanol. It also specifies the advantages and disadvantages of its use both in mixtures and in its pure form. The article also reviews the experimental analysis of emissions in the driving cycle fuel consumption of butanol. Mixtures of butanol – gasoline 5%, 30%, 50%, 85% and 100% were selected as a fuel without further additions as compared to the automotive gasoline and ethanolic E85. Switching to fuel based butanol in FFVs is not a technical problem, particularly based on the comparison with its demonstrable benefits over bioethanol. The development of renewable sources of carbohydrates from agricultural crops butanol can also help reduce imports of petroleum fuels in support of agriculture, availability of drinking water and an increase employment in the region.

Key words: butanol, bioethanol, gasoline, emissions, water.

INTRODUCTION

Biofuels have become an integral part of everyday life in modern society. Bioethanol and methyl esters of fatty acids are a regular part of producers of gasoline and diesel fuels, although in limited quantities, but intense pressure on replacing fossil fuels with bio-components constantly growing. Despite the considerable problems associated with high production costs, technical and logistical problems and negative impact on food prices in the first case of biofuels generation biofuel development is directed to the second generation, whose resource base is agricultural non-food biomass and waste. Among biofuels second generation is sorted and butanol (Šebor et al., 2006).

BioButanol (n-Butanol, Butan-1-ol) is an alternative to bioEthanol, which is currently commercially produced and used as a component of motor gasoline or as

E85. BioButanol has not only a higher calorific value than bioethanol, is not hygroscopic, but its characteristics even closer to gasoline and can be used as 100% bioButanol fuel (Pospíšil et al., 2014).

Traditional materials for the production of butanol are starchy crops (cereals, maize, potatoes) and molasses from sugar cane or sugar beet. In consideration, however, susceptible to other alternative materials such as whey, waste glycerol or unicellular algae accumulating starch in their cells.

Large positive or negative emotions currently produce the second generation biofuels (especially ethanol but also butanol), in the manufacture of which is the main source of cellulose saccharidic of different materials, e.g. straw or waste paper waste and energy crops. The release cellulose from lingocellulosic matrix and its subsequent cleavage to glucose units either chemically or enzymatically but the raw material compared to conventional sources saccharidic more costly (Patáková et al., 2010)

Selection of raw material depends on the enzymatic equipment of microorganisms. Cultures of Clostridium acetobutylicum and C. beijerinckii are capable of use as a substrate a variety of monosaccharides, disaccharides, and unlike yeasts and polysaccharides (starch). They have the enzymatic equipment for fermentation polysaccharides type of cellulose and hemicellulose . Such materials must first be subjected to hydrolysis to simple sugars by the action of hydrolytic enzymes or dilute acids (Ezeji et al., 2007; Melzoch & Rychtera, 2012).

Raw materials for ABE fermentation are distinguished:
1) starchy (potatoes, corn, wheat, rice);
2) sugary (sugar beet molasses, whey);
3) lignocellulosic (straw, wood).

Since in the original raw sugar and starchy raw material accounted for about 60% of the cost of producing butanol, looking for the cheap raw materials such as lignocellulosic materials and waste products of industrial production rich in carbohydrates, which would significantly reduce costs. Unlike yeast, clostridia are capable of producing solvent ferment greater variety of carbohydrates. Of the monosaccharides are hexoses (glucose, galactose), but also pentoses (xylose, arabinose, ribose), disaccharides (sucrose, mannose) and polysaccharides (starch). (Groow et al., 1992; Campos et al., 2002). In Table 1 are shown the dominant parameters ethanol and butanol in comparison with gasoline parameters. Table 2 shows dependence of the calorific value of gasoline on the content of ethanol and butanol.

In the evaluation of usable fuel in terms of energy content are distinguished and specific terms of energy consumption. The usable heat energy contained in the fuel is expressed either by referring to a unit mass of the fuel heating value is called the weight of the unit kJ kg^{-1}, or less frequently by referring to the unit volume of fuel, then it is a volumetric calorific value, reported in units of kJ kg^{-1}. (Hromádko et al., 2011). The total thermal energy of the fuel is expressed as heat of combustion, which can be described as all the energy obtained by burning 1 kg of fuel, including cooling the flue gas to the original temperature. The gases are of course in automotive engines emitted into the air so that condensation energy contained therein is not used. Utilised amount of energy is then expressed as calorific value, which is always less than the heat of combustion. (Mužíková et al., 2010). Gasoline with a density of 762 kg m^{-3} has

a calorific value of approximately 42.6 MJ kg^{-1}. Butanol has a lower calorific value than gasoline, but higher than the 14.5% ethanol.

Table 1. Comparison of basic parameters ethanol, n-Butanol and the gasoline fuel

Parameter	Ethanol	Butanol	Gasoline
Chemical formula	C_2H_5OH	C_4H_9OH	$CH_{1.87}$
Density at 15 °C(kg dm^{-3})	0.79	0.81	~ 0.73
Kinematic. viscosity at 20°C (mm^2 s^{-1})	1.52	3.64	0.4–0.8
Boiling point (°C)	78	118	30–215
Calorific value (MJ kg^{-1})	26.8	32.5	42.9
Heat of vaporization (MJ kg^{-1})	0.92	0.43	0.36
Vapor pressure (kPa)	19.3	18.6	60–90
Mixed octane number			
RON	106–130	94	95
MON	89–103	80–81	85
Oxygen content (% by weight)	34.7	21.6	< 2.7

The aim of the measurements referred to in article is to evaluate the fuel properties of a mixture of biobutanol with gasoline compared to E85 fuel and gasoline and emission analysis of these mixed fuels and pure gasoline.

Table 2. The dependence of the calorific value of gasoline on the content of ethanol and butanol

The oxygen content in gasoline (% by weight)	The ethanol content in gasoline (% v/v)	Calorific value gasoline with CH_3OH (MJ l^{-1})	The n-Butanol content in gasoline (% v/v)	Calorific value gasoline with C_4H_9OH (MJ l^{-1})
0	0	32.9	0.0	32.9
0.4	1	32.8	1.6	32.8
1.1	3	32.5	4.8	32.6
1.8	5	32.3	8.0	32.4
3.7	10	31.7	16.0	31.9
2.7	7.3	32.0	11.7	32.2

MATERIALS AND METHODS

To evaluate the effect of n-Butanol on gasoline parameters were selected mixed with the working title:

BUT 5: mixture of 5% n-Butanol and 95% gasoline;
BUT 30: mixture of 30% n-Butanol and 70% gasoline;
BUT 50: mixture of 50% n-Butanol and 50% gasoline;
BUT 85: mixture of 85% n-Butanol and 15% gasoline;
BUT 100 100% n-Butanol.

For experiments was used gasoline internal combustion engine Skoda Fabia 1.2 HTP, whose basic parameters are listed in Table 3.

Table 3. The parameters of the test engine

Engine code	AWY (BMD)
Construction	3 cylinder in-line engine 2 valves per cylinder
Stroke volume	1,198 (cm^3)
Cylinder Bore	76.5 (mm)
Stroke	86.9 (mm)
Compression ratio	10.3 : 1
Max power	40 (kW) by 4,750 (1 min^{-1})
Max torque	106 (Nm) by 3,000 (1 min^{-1})
Engine control unit	Simos 3PD (multipoint injection)
Fuel	gasoline 95
Emission standard	EU4
CO_2 emissions	142 (g km^{-1})

Measurements under laboratory conditions was carried out on a test bench (Fig. 1), which was placed above the internal combustion engine.

In Table 4 are shown the dominant parameters of swirl dynamometr. To evaluate the immediate emissions, an emission analyser VMK was used (Fig. 2). Detailed technical parameters are listed in Table 5. The instrument is designed to measure the concentrations of carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), nitrogen oxides (NO_X) and oxygen (O_2) in the exhaust gases of internal combustion engines with internal combustion mixture.
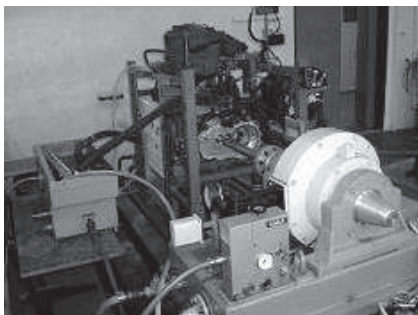
Figure 1. Swirl dynamometer.

Figure 2. Emission analyzer VMK.

Table 4. Parameters of swirl dynamometer

Dynamometer		Tensometer	
Type	V125	Rated load (kN)	2
Performance	IP23/ICW37	Combined error (%)	0.5
Engine speed (1 min^{-1})	300 – 2,500–8,000	Reproducibility (%)	0.05
Torque (Nm)	134 – 478–149.5		
Power (kW)	4.2 – 125–125		
Water flow (l/s)	0.9		
Input voltage (V)	91		
Input current (A)	1.7		
Water pressure (kPa)	90		
Weight (kg)	550		
EN	350,000		

Table 5. Parameters of emission analyser

Measured values	Measurement range	Resolution	Accuracy
CO	0–10% Vol.	0.01% Vol.	0–0,67% : 0,02% absolute 0.67% − 10%: 3% measured values
CO_2	0–16% Vol.	0.1% Vol.	0–10% : 0.3% absolute, 10–16% : 3% m. v.
HC	0–20,000 ppm	1 ppm	10 ppm or 5% m. v.
NO_X	0–5,000 ppm	1 ppm	0–1,000 ppm: 25 ppm 1,000–4,000 ppm: 4% m. v.
O_2	0–22% Vol.	0.1% Vol.	0–3%: 0.1% absolute 3–21%: 3% m. v.

The device has been modified so that it can be used for continuous measurement over a longer period of time to measure road or rail vehicles in operation (or other machines equipped with an internal combustion engine). It was also on the bench used diagnostic VAG-COM, which were scanned using the instantaneous value of the engine control unit. Fuel consumption was assessed by gravimetric method. Due to the complex design of modern internal combustion engines, fuel consumption was evaluated by weighing the whole fuel tank including the accessories. The fuel consumption is then evaluated as a weight loss of fuel in the tank (Fig. 10).

An additional control unit by Czech manufacturer EUROPECON MPI-A4 (Fig. 3) was used for adjusting the engine for biofuels. The unit is handling the adjustment of opening time of injectors so a biofuel's different energy per unit volume is compensated. Other unit's job is to provide improve starting of the cold engine by using additional saturation in dependence on the engine's temperature. It is possible to set the starting dose (for starting the engine) and also the saturation when the engine is cold.

Figure 3. Additional control unit for E85.
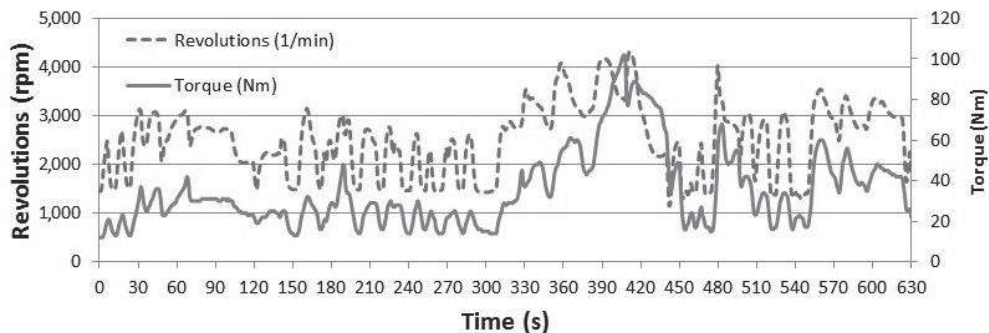
Figure 4. Sample of the driving cycle.

RESULTS

According to current standards for measuring automotive fuels and associated requirements and test methods were performed laboratory analysis of the fuels as a prerequisite for emission analysis. Measured parameters are shown in Table 6.

Table 6. Measured parameters of mixture gasoline with n-Butanol

Parameter	Unit	BUT 5	BUT 30	BUT 50	BUT 85	BUT 100
Density by 15°C	kg m^{-3}	736.16	781.5	786.01	802.95	818.1
Beginning of the distillation	°C	33	33	35	40	117
Evaporated by 70°C	% (V/V)	28	20	18	*	*
Evaporated by 100°C	% (V/V)	51	44	33	12	*
Evaporated by 150°C	% (V/V)	85	*	*	*	*
End distillation	°C	185	117	117	117	117
The distillation residue	% (V/V)	1.2	1.8	2.3	3.2	4.5
Vapor pressure	kPa	48.0	41.5	35.5	26.0	18.5
Index volatility	-	676.0	554.5	482.3	**	**
Viscosity by 40°C	mm^2 s^{-1}	0.67	0.86	1.02	1.69	2.43
Flash-point	°C	**	**	**	**	41

*value does not exist;
**parameter cannot be evaluated in accordance with the applicable measurement methods for liquid fuels and petroleum products.

The resulting emissions and fuel consumption (Table 7) are based on the driving cycle of the vehicle. Designed driving cycle based on real driving of the vehicle and is adapted to the conditions of the brake post. It is defined by the preset course of the torque and engine revolutions versus time (10.5 minutes). Fig. 4 shows sample of the driving cycle.

Table 7. Results emission analysis of the fuels

Fuel	Emissions	CO	CO$_2$	NO$_x$	HC
B5	sum. driving cycle (g)	31.81	1,911	3.28	0.185
	avg. (g hr^{-1})	3.03	182	0.31	0.018
B30	sum. driving cycle (g)	19.19	1,911	4.20	0.150
	avg. (g hr^{-1})	1.83	182	0.40	0.014
B50	sum. driving cycle (g)	14.74	1,912	11.98	0.209
	avg. (g hr^{-1})	1.40	182	1.14	0.020
B85	sum. driving cycle (g)	10.47	1,913	13.63	0.212
	avg. (g hr^{-1})	1.00	182	1.30	0.020
B100	sum. driving cycle (g)	9.56	1,825	12.60	0.186
	avg. (g hr^{-1})	0.91	174	1.20	0.018
E85	sum. driving cycle (g)	31.85	1,901	4.48	0.296
	avg. (g hr^{-1})	3.03	181	0.43	0.028
Gasoline	sum. driving cycle (g)	34.83	1,924	3.48	0.208
	avg. (g hr^{-1})	3.32	183	0.33	0.020

The following Figs 5, 6, 7, 8 and 9 show the sum of values recorded for the entire driving cycle.
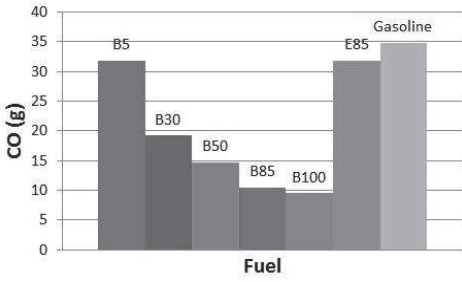
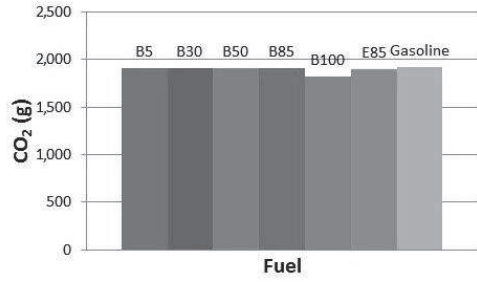**Figure 5.** CO emissions in the driving cycle (g).

Figure 6. CO_2 emissions in the driving cycle (g).
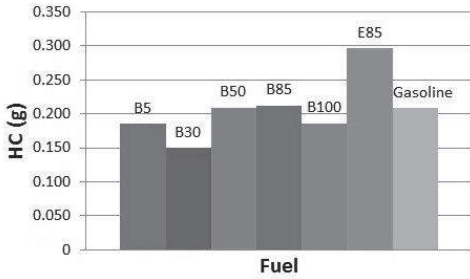

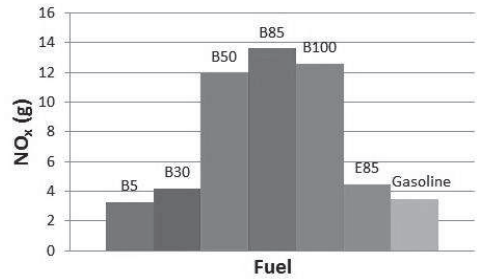**Figure 7.** HC emissions in the driving cycle (g).

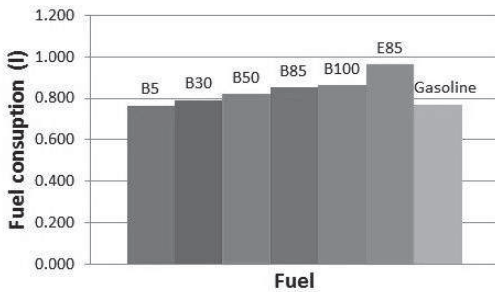**Figure 8.** NO_x emissions in the driving cycle (g).

Figure 9. Fuel consumption in the driving cycle (l).

Figure 10. Position of the tank on the platform scale.

As shown in Fig. 5, with an increasing rate of butanol decreases the production of CO. In the case of production of CO_2 can be stated, that there is no fundamental differences between the tested fuels. For the production of NO_x can be seen (Fig. 8), that with increasing proportion butanol increasing NO_X production, which can be attained due to the higher temperature combustion. HC emissions do not show significant differences between the compared fuels production were achieved on the accuracy of the measuring device and the results of the emission component can be taken for reference only. Last Fig. 9 illustrates the results achieved fuel consumption. It is evident, that an increasing share of butanol take to improve fuel consumption. This is primarily due to the calorific value of the fuel used.

CONCLUSIONS

It can be said that the plant fuel, ethanol and butanol are purposefully added to gasoline. Butanol as an alternative to bioethanol for use of biofuels in transport. Subject to the requirements of EN 228 for the maximum permissible oxygen content in gasoline butanol can be added to the gasoline in volume more than twice the amount of ethanol. Addition of butanol in an amount of 10% (v/v) in gasoline not jeopardize compliance limits according to EN 228, in terms of density, vapor pressure and oxidation stability. Butanol is compared with ethanol better fuel properties – higher heating value, lower vapor pressure, lower heat of vaporization and does not problems with water in the fuel. Both fuels can be produced from the same plant raw material, but the production of butanol is costly. Growing consumer interest in access and butanol stimulate the activity in agriculture and industry. This will affect the growth of production and reduce production costs. Expected future increases in fossil fuel prices and purity requirements combustion and low emissions should be reflected in an increase in the volume of production of butanol. From the viewpoint of fuel properties represents butanol (n-Butanol) preferable alternative to bioethanol and give primarily burn even in its pure form as a 100% biofuel.

REFERENCES

Campos, E.J., Qureshi, N. & Blashek, H.P. 2002. Production of acetone Butanol ethanol from degermed corn using Clostridium beijerinckii BA 101, Applied Biochemistry and Microbiology, pp. 553–556.

EN 228. 2009. *Automotive fuels – Unleaded petrol – Requirements and test methods*, ČSNI, 16 pp. (in Czech).

Ezeji, T., Qureshi, N. & Blashek, H.P. 2007. Butanol production from agricultural residues: impact of degradation product on Clostridium beijerinckii growth and Butanol fermentation. Biotechnology & Bioengineering, Wiley, pp. 1460–1469.

Groot W.J., Lans, R.G.J.M. & Luyben, K.Ch.A.M. 1992. Technologies for Butanol Recovery Integrated with Fermentations, Process Biochemistry 27, pp. 61–75.

Hromádko, J., Hromádko, J., Miler, P., Hönig, V. & Štěrba, P. 2011. The use of bioethanol in internal combustion engines. *Chemické listy* **105**(2), 122–128.

Melzoch, K. & Rychtera, M. Distillery and production of spirits: sylabus [online]. [cit. 2012-11-21], Available at: http://www.vscht.cz/kch/kestazeni/sylaby/liho.pdf

Mužíkova, Z., Pospíšil, M. & Šebor, G. 2010. The use of bioethanol as a fuel in the form of E85 fuel. *Chemické listy* **104**(7), 678–683 (in Czech).

Patáková, P., Pospíšil, J., Lipovský, J, Fribert, P., Linhová, M, Toure, S.S.M., Rychtera, M., Melzoch, K. & Šebor, G. 2010. Prospects for biobutanol production and the use in the Czech republic, *Chemagazín*. **20**(5), 13–15.

Pospíšil M., Šiška, J. & Šebor, G.: BioButanol as fuel in transport, Biom [online]. [cit. 2014-17-01]. Available at www: biom.cz.

Šebor, G., Pospíšil, M. & Žákovec, J.: Technical and economic analysis of suitable alternative transport fuels, research report prepared for the Ministry of Transport, ICHT Prague, June (2006). [online]. [cit. 2012-11-09], available from:
http://www.mdcr.cz/cs/Strategie/Zivotni_prostredi/