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The operational parameters and emissions of portable generator after long-term operation on n-butanol

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Abstract. The utilization of biofuels in spark ignition and compression ignition engines is the trend of the recent time. The great expectations are inserted into n-butanol as a fuel, especially for spark ignition engines. The short time use of n-butanol in the SI (spark ignition) combustion engine does not make a big problem (start of the cold engine, change of the air-fuel ratio). The purpose of this contribution is the effect of long-term use of n-butanol as a fuel for SI engine. For this purpose the small portable generator was used. The harmful emissions, fuel consumption and power of the generator was measured then the generator was operated for 300 hours on 100% n-butanol with 80% of nominal load and the measurement was repeated. The generator was loaded with adjustable electrical resistance. As a reference fuel the petrol BA 95 with no bio-component was used. During the operation on n-butanol no technical problems occurred with the generator. After 300 hours of operation on n-butanol the performance parameters slightly decreased with little impact on production of harmful emissions components.

Key words: biofuel, petrol, emission, fuel consumption, spark ignition.

INTRODUCTION

In the present time, combustion of conventional fossil fuels such as petrol and diesel fuel represents more than half of the world's primary energy consumption. The use of the biofuels helps to reduce the consumption of fossil fuels and amount of greenhouse gasses released into atmosphere and also helps to ensure the energy security (Awad et al., 2018).

The alcohol based biofuels are the most widely used for SI engines. Ethanol, the most used biofuel for SI engines, 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; Gailis & Pirs, 2017).

N-butanol could be used as an alternative to ethanol as alcohol-based biofuel. The n-butanol is the second generation biofuel. In many studies the utilization of n-butanol in CI (compression ignition) as a fuel admixture is studied. In CI engines the n-butanol is usually utilized to decrease the viscosity of the fuel blends with higher concentrations of biodiesel or vegetable oil (Rakopoulos et al., 2010; Yilmaz et al., 2014; Atmanli et al., 2015; Čedík et al., 2015; Pexa et al., 2016; Babu et al., 2017; Peterka et al., 2017).

The n-butanol can be produced similarly to ethanol, by fermentation or in petrochemical way (Ezeji et al., 2003; Ndaba et al., 2015; Rocha–Meneses et al., 2017). Compared with ethanol the properties of n-butanol are closer to petrol due to the longer hydrocarbon chain. However, similarly to ethanol, the use of 100% n-butanol in spark ignition engines also requires the modification of the air-fuel mixing ratio, due to lower stoichiometric ratio of n-butanol. In comparison with the ethanol, the n-butanol has several advantages, such as a lower ignition temperature and higher calorific value. Also, compared with ethanol, the n-butanol has better mixing properties with hydrocarbon fuels and due to lower oxygen content the stoichiometric ratio is more similar to petrol. Therefore, the higher concentrations of n-butanol in petrol without engine modification can be used. The n-butanol is also less corrosive due to lower affinity to water than ethanol (Qureshi & Ezeji, 2008; Shapovalov & Ashkinazi, 2008; Andersen et al., 2010; Harvey & Meylemans, 2011; Swana et al., 2011; Gu et al., 2012; Serras-Pereira et al., 2013; Hönig et al., 2015a; 2015b; Yusri et al., 2016; Peterka et al., 2017). Petrol blended with n-butanol was studied in the various range of mixing ratios up to 100% of n-butanol (Wallner 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; Yusri et al., 2016; Peterka et al., 2017; Yusoff, et al., 2017). The results of these studies show that, in comparison with petrol, fuel blended with n-butanol reduces the emissions of carbon monoxide and unburned hydrocarbons, emissions of carbon dioxide and nitrogen oxides could be decreased or increased (Peterka et al. 2017). Due to the lower calorific value compared with petrol the specific fuel consumption is higher and the torque and power are lower. Better combustion efficiency can be achieved due to better anti-detonation characteristics of n-butanol compared with petrol and higher oxygen content. Yusri et al. (2016) found that the addition of n-butanol into the petrol in concentration up to 15% decreases the cylinder pressure, emissions of CO, NO_X and exhaust gas temperature. Some sources indicate the increased torque and reduced energy consumption at 35% concentration of n-butanol in petrol (Feng et al., 2013). Other sources state that the performance parameters of the engine are maintained the same in concentration range from 10% (Kukharonak et al., 2017) to 20% (Yang et al., 2009) of n-butanol in the petrol. Peterka et al. (2017) found increased emissions of NO_X, especially at low and moderate engine load, decreased emissions o CO and HC, slightly increased emissions of CO_2, especially in lower engine load, and increased fuel consumption.

Most of the above mentioned studies were carried out in short term measurement and does not take into account the effect of long term operation of the engine.

The aim of the paper is to compare the emission production and fuel consumption of the generator when operating on n-butanol and petrol BA 95 after 300 operating hours with approx. 80% of nominal load. The harmful emissions components (CO – carbon monoxide, CO_2 – carbon dioxide, NO_X – nitrogen oxides, HC – hydrocarbons and PM – particulate matter) and fuel consumption are monitored and compared with the results, obtained after 5 operating hours.

MATERIALS AND METHODS

The two mobile generators ProMax 3500A (Fig. 1, Table 1). The combustion engine, connected to the alternator is suitable for long-time tests since the engine can be easily loaded and the electrical output power of the generator is equivalent to the engine load.

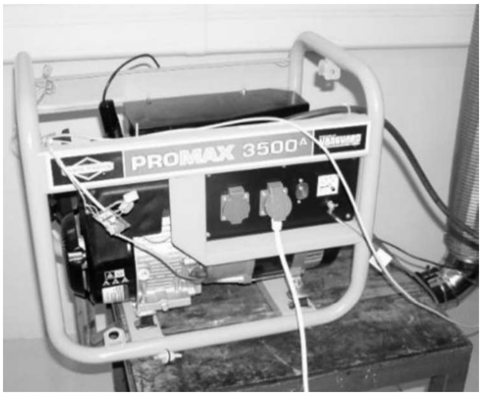

Figure 1. Mobile generator ProMax 3500A powered by small Briggs and Stratton engine type Vanguard 6.5HP.

Table 1. Basic specification of the used generators

Electrical parameters	
Parameter	**Specification**
Manufacturer	Briggs and Stratton
Type	ProMax 3500A
Rated power	2,700 W
Maximum power	3,400 kVA
Output voltage	220 V
Output frequency	50 Hz
Output current	11.2 A
Engine parameters	
Parameter	**Specification**
Manufacturer	Briggs and Stratton
Type	Vanguard 6.5HP
Rated power	4.8 kW at 3,600 min^{-1}
Max. torque	13.3 Nm at 3,000 min
Engine type	4-stroke, spark ignitio
Displacement	205 cm^3
Cooling	Air cooled
Bore X Stroke	68.3 X 55.9 mm
Compression ratio	8.3:1
Valves	2
Valve mechanism	OHV
Lubrication	Splash
Crankshaft orientanion	Horizontal

Table 2. Parameters of the emission analyser 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

The measurement is focused on the comparison of fuel consumption and emissions production of the combustion engine of the generator before and after its long time operation on petrol BA 95 and n-butanol. Two generators were used in the study, one for each fuel. Before the test the generators were new. The measurement was carried out after 5 operating hours and after 300 operating hours of the engine with 80% of nominal load of the generator.

During loading of the combustion engine the frequency, electrical current and voltage of the output of the generator are measured using the electrometer ZPA ED310 equipped with an RS 485 (accuracy of 0.05%). Simultaneously with the measurement of electrical parameters fuel mass flow rate using Vibra AJ 6200 standard precision scale (accuracy 0.1 g) is also measured. 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 and EEPS particle analyser are used as testing devices of emissions (Table 2). All data are stored to the PC memory using

RS482 to RS232 interface and for this purposes software application was developed in LabView.

The values of emissions production are measured in volumetric concentrations and, based on the amount of the intake air, they are recalculated into mass production.

The principle of the measurement is similar to that used by Peterka et al. (2017). The combustion engine of the generator works at the rotation speed of 3000 min^{-1} (electrical output frequency of 50 Hz). In this rotation speed the engine is gradually loaded by electrical resistance to the power of approx. 660, 1,320, 1950 and 2,560 W. Under these loads, which corresponds to 25, 50, 75 and 100% of the nominal power of the generator, the measurements are performed with petrol BA 95 (with no ethanol) and with 100% n-butanol (BUT). The basic parameters of the fuels are listed in Table 3.

Table 3. Basic properties of used fuels (Feng et al., 2015; Elfasakhany & Mahrous, 2016)

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 (%)	21.6	–
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	11.21	14.7
Octane number	96	86–94
Boiling temperature (°C)	117.7	25–275
Adiabatic flame temperature (K)	2,340	2,370
Saturation pressure at 38 °C (kPa)	2.27	31.01

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

The air–fuel ratio (AFR) was monitored within the measurement. Then, the AFR was modified using the fuel choke. AFR for petrol BA 95 is 14.7:1 and 11.2:1 for n-butanol (Elfasakhany & Mahrous, 2016).

RESULTS AND DISCUSSION

The result values of emission components, fuel consumption, rotation speed and engine load are the mean values from two minutes record with frequency of 1 Hz. The emissions of particulate matter were excluded from the data evaluation. The concentration of particulate matter in the exhaust gas of the spark ignition engine is very low and from the viewpoint of measurement device it is at the limit of detection.

In the Table 4 the volumetric concentrations of emission components in the exhaust gas of combustion engine of the generator after 5 operating hours are shown. The grey areas in the tables highlights the lower value of harmful emissions production or fuel consumption in comparison between the used fuels. The volumetric concentrations of emission components in the exhaust gas after 300 operating hours are shown in the Table 5.

Table 4. Fuel consumption and volumetric concentrations of the emissions components in the exhaust gas of the combustion engine after 5 operating hours for BA 95 and BUT fuels. (FC – fuel consumption; SFC – specific fuel consumption) (Peterka et al., 2017)

	Engine speed	Output power	NO_X	CO	CO_2	HC	FC	SFC
	min^{-1}	W	ppm	%	%	ppm	$g\ h^{-1}$	$g\ kWh^{-1}$
BA 95	3,142.95	656.10	88.86	3.82	7.91	104.06	600.12	914.67
	3,121.01	1,331.87	175.90	3.92	7.74	120.48	789.39	592.70
	3,101.91	1,939.89	363.21	4.09	8.61	129.40	960.29	495.02
	2,989.63	2,566.52	660.79	4.68	10.56	137.27	1,162.49	452.94
BUT	3,141.04	656.65	155.19	0.77	9.65	44.32	665.77	1,013.89
	3,122.16	1,330.26	361.20	1.59	9.35	56.11	882.97	663.76
	3,091.03	1,941.19	714.57	2.08	9.82	77.86	1,106.60	570.06
	2,915.82	2,591.58	818.34	3.35	11.26	90.86	1,408.77	543.59

From the Table 4 and 5 it is evident that after 300 operating hours the BUT fuel reached better values in terms of emissions of nitrogen oxides and carbon dioxide. On the other hand, the fuel BA 95 reached better results in emissions of carbon monoxide and unburned hydrocarbons. The fuel consumption was increased for both tested fuels, n-butanol and petrol, but for the n-butanol the fuel consumption increase is more significant.

Table 5. Fuel consumption and volumetric concentrations of the emissions components in the exhaust gas of the combustion engine after 300 operating hours for BA 95 and BUT fuels. (FC – fuel consumption, SFC – specific fuel consumption)

	Engine speed	Output power	NO_X	CO	CO_2	HC	FC	SFC
	min^{-1}	W	ppm	%	%	ppm	$g\ h^{-1}$	$g\ kWh^{-1}$
BA 95	3,124.45	681.28	82.41	2.56	6.37	76.21	884.4	1,298.14
	3,122.32	1,333.46	129.83	3.2	6.74	90.03	825.6	619.14
	3,041.81	1,949.28	255.98	3.1	7.29	98.82	972	498.65
	2,862.39	2,605.51	611.55	3.12	8.93	98.17	1,203.6	461.94
BUT	3,138.58	680.26	40.14	3.57	6.27	118.97	807.6	1,187.2
	3,117.1	1,333.1	44.58	4.43	5.94	132.98	1,094.4	820.95
	3,009.68	1,958.33	30.97	6.45	5.68	211.14	1,423.08	726.68
	2,941.71	2,298.51	84.35	5.1	6.81	178.72	1,399.5	608.87

Also, it may be noted that the maximum electric output power of the generator decreased by approx. 11% after 300 operating hours on n-butanol.

The mass production of the harmful emissions components is shown in the Table 6 (after 5 operating hours) and in the Table 7 (after 300 operating hours). The mass production of emissions components was calculated based on fuel consumption and AFR ratio.

Table 6. Mass production of the emissions components in the exhaust gas of the combustion engine after 5 operating hours for BA 95 and BUT fuels. (FC – fuel consumption, SFC – specific fuel consumption) (Peterka et al., 2017)

	Engine speed	Output power	NO_X	CO	CO_2	HC
	min^{-1}	W	$g\ h^{-1}$	$g\ h^{-1}$	$g\ h^{-1}$	$g\ h^{-1}$
BA 95	3,142.95	656.1	0.8	0.032	1,040.34	1.37
	3,121.01	1,331.87	2.08	0.043	1,340.4	2.09
	3,101.91	1,939.89	5.21	0.055	1,813.84	2.73
	2,989.63	2,566.52	11.48	0.076	2,690.74	3.51
BUT	3,141.04	656.65	1.26	0.006	1,150.4	0.53
	3,122.16	1,330.26	3.89	0.016	1,477.1	0.89
	3,091.03	1,941.19	9.65	0.026	1,945.88	1.55
	2,915.82	2,591.58	14.07	0.054	2,838.27	2.3

Table 7. Mass production of the emissions components in the exhaust gas of the combustion engine after 300 operating hours for BA 95 and BUT fuels. (FC – fuel consumption, SFC – specific fuel consumption)

	Engine speed	Output power	NO_X	CO	CO_2	HC
	min^{-1}	W	$g\ h^{-1}$	$g\ h^{-1}$	$g\ h^{-1}$	$g\ h^{-1}$
BA 95	3,124.45	681.28	1.6	0.032	1,234.76	1.48
	3,122.32	1,333.46	2.35	0.037	1,220.86	1.63
	3,041.81	1,949.28	5.46	0.042	1,554.08	2.11
	2,862.39	2,605.51	16.14	0.052	2,357.28	2.6
BUT	3,138.58	680.26	0.58	0.033	905.89	1.72
	3,117.1	1,333.1	0.87	0.055	1,163.03	2.61
	3,009.68	1,958.33	0.79	0.105	1,447.42	5.39
	2,941.71	2,298.51	2.11	0.081	1,704.86	4.49

Table 8. The percentage comparison of mass emissions production and fuel consumption after 5 operating hours (100%) and after 300 operating hours for BA 95 and BUT fuels. (FC – fuel consumption, SFC – specific fuel consumption)

	No.	Engine speed	Output power	NO_X	CO	CO_2	HC	FC	SFC
	-	%	%	%	%	%	%	%	%
BA 95	1	99.41	103.84	200.47	98.81	118.69	107.93	147.37	141.92
	2	100.04	100.12	113.23	85.52	91.08	78.16	104.59	104.46
	3	98.06	100.48	104.64	76.69	85.68	77.30	101.22	100.73
	4	95.74	101.52	140.55	69.08	87.61	74.05	103.54	101.99
BUT	5	99.92	103.59	46.03	563.49	78.75	325.62	121.30	117.09
	6	99.84	100.21	22.44	345.47	78.74	293.74	123.95	123.68
	7	97.37	100.88	8.18	399.20	74.38	348.74	128.60	127.47
	8	100.89	88.69	15.02	151.31	60.07	195.41	99.34	112.01

The percentage comparison of the mass production of harmful emissions and fuel consumption of the engine after 5 operating hours (100%) and after 300 operating hours is shown in the Table 8. Also, the decrease of the maximum output power of the generator to the value of 2.3 kW in the case of n-butanol has to be taken into account. The value, measured after 5 operating hours (2.6 kW), was not reached. This point has number 8 in the Table 8. From the comparison of the engine speed and output power it is evident that the very similar operating condition were reached. The highest deviation of speed is approx. 4% and the highest deviation of output power is 11% (at point no. 8). At other points the deviation of output power did not exceed 4%, as in the case of the engine speed.

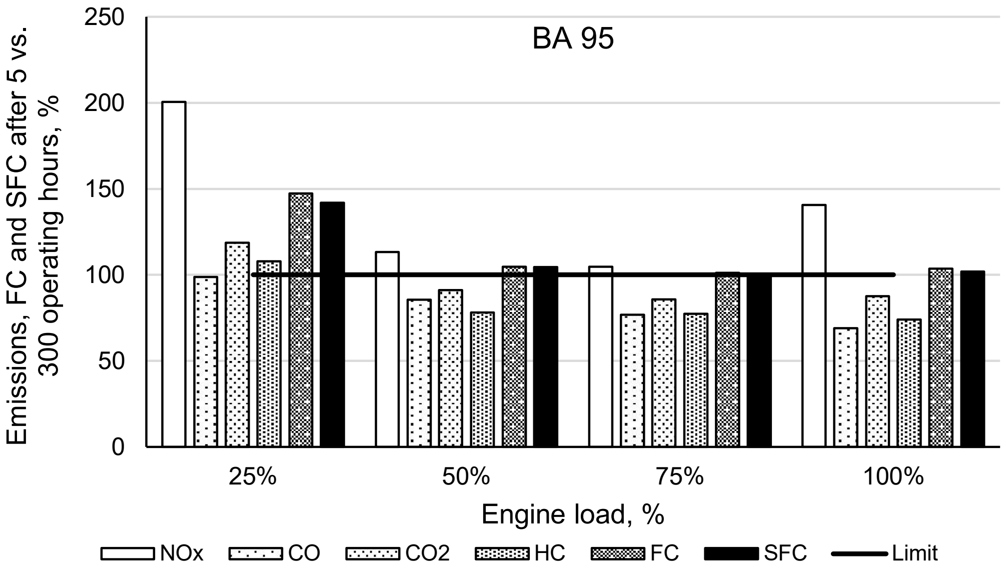

Figure 2. Percentage comparison of emissions production and fuel consumption of the generator oprerating on petrol (BA 95) after 5 operating hours (100%) and 300 operating hours. (FC – fuel consumption, SFC – specific fuel consumption)

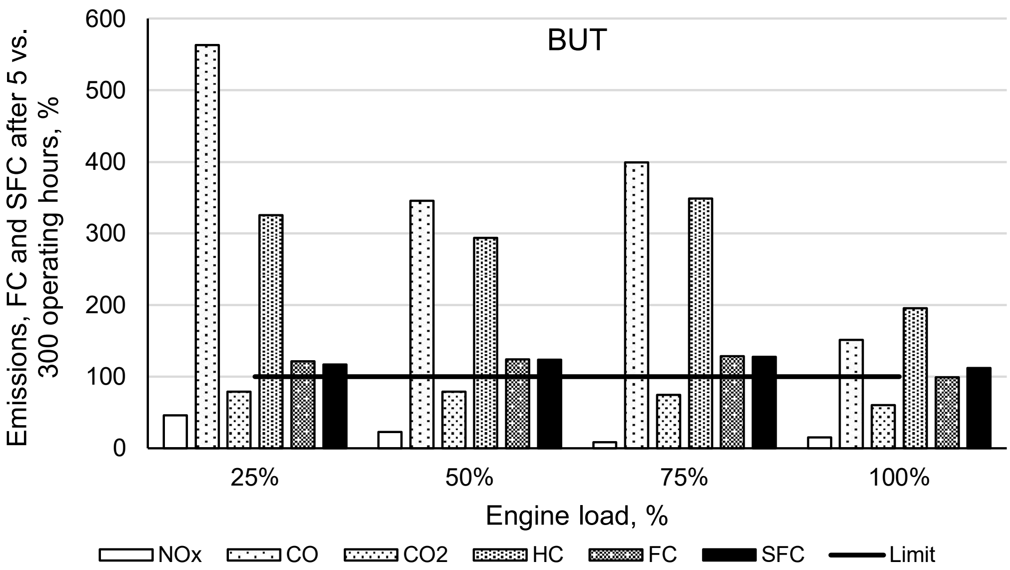

Figure 3. Percentage comparison of emissions production and fuel consumption of the generator oprerating on n-butanol (BUT) after 5 operating hours (100%) and 300 operating hours. (FC – fuel consumption, SFC – specific fuel consumption).

The result values of the percentage comparison, are also shown in graphical form in the Fig. 2 (BA 95) and Fig. 3 (BUT). In more detail, it can be stated that after 300 operating hours in all measured points the increase of the fuel consumption was reached with both fuels, BA 95 and BUT. After 300 hours of operation on BA 95 all of the monitored emission components, except CO, were increased at approx. 25% engine load (point no. 1). At other engine loads (approx. 50%, 75% and 100% – points 2, 3 and 4 in Table 8) the emissions of HC, CO_2 and CO were decreased and the emissions of NO_X were increased in comparison with the results, obtained after 5 operating hours.

After 300 operating hours on BUT fuel the emissions of NO_X and CO_2 were reduced and the the emissions of CO and HC were increased at all engine loads. The emissions of NO_X were reduced by up to 91.8% (at 75% load – point no. 7 in Table 8), however, the emissions of CO were increased on average 3.6 times and emissions of HC on average 2.9 times in comparison with the results, obtained after 5 operating hours. Increased emissions of CO and HC and decreased emissions of CO_2 indicates worsened combustion efficiency. Also, the decreased NO_X emissions indicates lower combustion temperature. This result could be explained by the aggressiveness of n-butanol to rubber sealing elements and plastic parts in the carburettor and therefore worsened mixture preparation.

CONCLUSIONS

The contributions provides a new information about the long-term operation of the combustion engine on n-butanol on its operational parameters. The measurements, focused on comparison of fuel consumption and emissions production (CO_2, CO, NO_X, HC) of combustion engine fuelled by carburettor (generator) during its operation on BA 95 and n-butanol (BUT) after 300 operating hours, reached following results:

- The fuel consumption was increased after 300 operating hours on both fuels BA 95 (on average by 14%) and BUT (on average by 18%).
- By use of BA 95 fuel the decrease of emissions production of HC (on average by approx. 15%), CO_2 (on average by approx. 4%) and CO (on average by approx. 17%) and the increase of NO_X emissions production (on average by approx. 40%) was reached at engine loads approx. 50%, 75% and 100% after 300 operating hours.
- By use of BUT fuel the decrease of emissions production of NO_X (on average by approx. 75%) and CO_2 (on average by approx. 25%) and increase of emissions production of CO (on average 3.6 times) and HC (on average 2.9 times) was reached at all measured engine loads (approx. 25%, 50%, 75% and 100%) after 300 operating hours.

In comparison with the results, obtained after 5 operating hours of generators the BUT fuel reached the higher fuel consumption (by approx. 25%), higher production of CO (by approx. 67%) and HC (by approx. 80%) after 300 operating hours. BA 95 fuel reached the higher production of NO_X (by approx. 70%) and CO_2 (by approx. 12% after 300 operating hours.

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