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Effect of long-term operation of combustion engine running on n-butanol – rapeseed oil – diesel fuel blend

M. Holúbek*, M. Pexa, J. Čedík and D. Mader

Czech University of Life Sciences Prague, Faculty of Engineering, Department for Quality and Dependability of Machines, Kamýcká 129, CZ165 21, Prague 6, Czech Republic
*Correspondence: holubekm@tf.czu.cz

Abstract. The short time use of biofuels in compression ignition engines is being studied by many authors. However, in many cases the real long–term operation of the engine on biofuels may cause problems. The article deals with the operation parameters of the combustion engine, fuelled by n-butanol – rapeseed oil – diesel fuel blend, during 70 hours operation in total. Two brand new diesel power generators Kipor KDE 6500 with output power of 4.6 kW were used for certain testing. The first generator was operated on 100% diesel fuel and it was used as a reference and the second generator was operated on experimental fuel containing 10% n-butanol – 20% rapeseed oil – 70% diesel fuel blend. The generators were equipped with single cylinder compression ignition engine Kipor KM 186 with the rated power of 5.7 kW. For the first 10 operating hours approx. 40% load was applied. Then, the generators worked for another 60 operating hours with approx. 70% load. The harmful emissions, smoke, fuel consumption and the amount of produced particles were also measured after 10 hours run-in period and then after another 60 hours of operation. Consequently, the results were compared. Measurements were carried out at gradually increasing electric power output, approx. 14%, 28%, 42%, 56%, 68%, 82% and 95% (in results can be found in Watts). Emission analyser and opacimeter BrainBee and Engine Exhaust Particle Sizer TSI were used for the measurements. The results showed increased production of emission of the engine running on fuel blend after 70 hours of operation. On the other hand, engine which operated on standard diesel reached lower fuel consumption. After 70 hours the blended fuel tended to produce more particles in comparison with diesel fuel.

Key words: emissions, fuel consumption, biofuels, power generator, particles, opacimeter.

INTRODUCTION

In order to reduce the use of diesel and its negative impact on the environment, renewable energy sources have been receiving much attention in recent years (Saadabadi et al., 2019). Utilisation of biofuel for internal combustion engines is gaining importance in the global energy policy, on the way to reduction of our dependency on fossil fuels. The most harmful products of diesel combustion engines are particles, smoke emissions and nitrogen oxides (Doğan, 2011; Pexa et al., 2016). The biomass based fuels can offer a feasible solution to the world's dependence on petroleum–based fuels and can provide advantages, such as environmental protection

and sustainability. Biofuels are almost free from sulphur, continually produced from vegetable matter and have low toxicity (Atmanli et al., 2015; Killol et al., 2019).
N-butanol is a promising next generation alternative fuel for stabilizing diesel fuel–vegetable oil blends at low temperatures. N-butanol represents a better alternative fuel than ethanol and methanol (lower alcohols). N-butanol is also a bio-origin renewable fuel that can be produced by alcoholic fermentation of biomass (Jin et al., 2011).

In comparison with other biofuels, 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. Butanol is less corrosive and better miscible with vegetable oils, diesel, etc. (Szwaja & Naber, 2010; Hönig et al., 2014; Peterka et al., 2016).

Butanol's chemical properties are closer to diesel fuel than to lower alcohols. Lower alcohols cause a longer ignition delay period of combustion because of their higher latent heat of vaporization and low ability to ignite (Mařík et al., 2014). Moreover, n-butanol shows appropriate combustion characteristics in diesel engines. Usage of n-butanol demands neither a cetane enhancing additive nor a solubilizer due to its relatively high cetane number, high solubility and no phase separation in diesel fuel (Siwale et al., 2013; Atmanli et al., 2015).

Vegetable oils, such as rapeseed oil, may be used in several ways while the modification of fuel or the fuel system is mostly required. Raw vegetable oil can be added into the diesel oil in ratio 20% oil and 80% diesel and it can be burned without modification of the engine (Pexa et al., 2015). The main advantage of using purified rapeseed oil is primarily its low price. The extraction and processing of vegetable oils are simple low energy processes that support agricultural production (Altin et al., 2001).

Vegetable oils are also degradable, renewable and they have positive energy balance. However it is necessary to respect the diversity of vegetable oil properties compared to diesel (heat of combustion, cetane number, freezing point, etc.) (Hönig & Hromadko, 2014). Due to their high viscosity and thickening in cold conditions, vegetable oil fuels still have problems with low flowing, atomization and heavy particle emissions. Maximum power and torque decrease due to a lower energy content of triacylglycerols (Kleinová et al., 2011). Vegetable oil blend may reduce unburned hydrocarbon and CO emissions. Effect on emission of NOx and particle matter and fuel consumption is less clear and appears to be dependent on test conditions (Gailis et al., 2017).

Although there are several valuable works concerning n-butanol–gasoline blended fuels in combustion engines, there is limited information of combustion characteristics over a range of blends of *n*-butanol and diesel including vegetable oils.

The aim of this paper was to compare fuel consumption and production of emissions of two generators when operating on blended fuel (containing 10% of n-butanol, 20% of rapeseed oil and 70% of diesel) and standard diesel as a reference in the same type of engine, operated with around 70% of its nominal load. Different effect of fuels on combustion engine was observed. The harmful emissions and fuel consumption were monitored after 10 and 70 hours of operation.

MATERIALS AND METHODS

For the experiment two mobile generators Kipor KDE 6500E were used (Fig. 1). Specifications of the generator are listed in Table 1. One generator was running on fossil diesel fuel with no bio-components and the second generator was running on biofuel blend. For the first 10 operating hours (run-in period) the generators were loaded by 2 kW (40%) according to the recommendation from the manufacturer. Then, the generators were loaded with approx. 3.2 kW (70% of the nominal output power) for 60 operating hours. During the long-term operation the generators were running for 70 operating hours. The rotation speeds of engines of generators were set by the build-in regulator and it should be kept constant at approx. 3,000 rpm. The build-in regulator was not modified.

Figure 1. Generator Kipor KDE 6500E.

The short-time measurements were performed after the first 10 operating hours and then after 70 operating hours. The measurements were performed at stable conditions (at least 2 minutes stabilization at each point) with gradually increasing loads, approx. 14%, 28%, 42%, 56%, 68%, 82% and 95%. After engine stabilization the measured parameters were recorded for approx. 1 minute. The engine was loaded using electrical heaters. The heaters have a scale with a step of approx. 650W and does not have specified accuracy of consumed power. The output electrical power (current, voltage and frequency) was measured using the electrometer ZPA ED310 equipped with an RS 485 (accuracy 0.05%).

For the mass fuel consumption measurement was used the standard precision scale Vibra AJ 6200 (accuracy 0.1 g, readability 0.01 g).

Table 1. Basic specification of generator Kipor KDE 6500E

Electrical parameters	
Parameter	Specification
Manufacturer	Kipor
Type	KDE 6500E
Rated power	4,600 W
Output voltage	220 V
Output frequency	50 Hz
Output current	19.6 A
Engine parameters	
Parameter	Specification
Manufacturer	Kipor
Type	KM 186FAG
Rated power	5.7 kW at 3,000 min^{-1}
Max. torque	18.7 Nm at 2,880 min^{-1}
Engine type	4-stroke, compression ignition
Displacement	418 cm^3
Cooling	Air cooled
Bore X Stroke	86 X 72 mm
Compression ratio	19:1
Valves	2
Valve mechanism	OHV
Lubrication	Combined
Crankshaft orientation	Horizontal
Fuel system	Mechanical injection pump
Start of injection	17° BTDC ± 1°

Data from laboratory scale and electrometer were transmitted to the PC memory using RS482 to RS232 interface and for that purpose developed software application in LabView.

For measurement of harmful gaseous emission components and opacity the emission analyser BrainBee AGS 200 and opacimeter BrainBee OPA 100 (Table 2) was used. The values of opacity were converted into mass concentration using the converting table, given by manufacturer. Engine Exhaust Particle Sizer 3090 (EEPS) made by TSI Inc. was used for analyse of solid particles, produced by engine. Specification of the EEPS is listed in Table 3. Before entering the EEPS the exhaust gas was diluted (dilution ratio = 0.0009702, dilution factor = 1030.8). Data from BrainBee emission analyser and opacimeter and from EEPS were stored via data acquisition units, provided by manufacturers.

Table 2. Basic specification of the BrainBee emission analyser and opacimeter

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

Table 3. Basic specification of the EEPS

Particle Size Range	5.6–560 nm
Particle Size Resolution	16 channels per decade (32 total)
Electrometer Channels	22
Charger Mode of Operation	Unipolar diffusion charger
Inlet Cyclone 50% Cutpoint	1 µm
Time Resolution	10 size distributions (s^{-1})

As a test blended fuel the n-butanol – rapeseed oil – diesel fuel blend was used, containing 10% of n-butanol, 20% of rapeseed oil and 70% of diesel. Diesel fuel with no bio-component was used as a reference. Basic specification of the fuels, used in experiment are shown in Table 4. Stabinger Viscometer SVM 3000 made by Anton Paar GmbH (measuring accuracy < 1%, repeatability 0.1%) was used for measurement of density and viscosity of the fuels. Isoperibol calorimeter LECO AC600 (measuring range 23.1–57.5 MJ kg^{-1} for a 0.35 g sample, accuracy 0.1% RSD) was used for measurement of calorific values of the used fuels according to standards ČSN DIN 51900-1 and ČSN DIN 51900-2. Cetane indexes of the fuels was calculated from distillation curves according to EN ISO 4264.

Table 4. Basic specification of used fuels

Fuel	Density at 15°C kg m^{-3}	Calorific value MJ kg^{-1}	Viscosity at 40 °C mm^2 s^{-1}	Cetane number -	Cetane index -
Diesel 100	819.13	43.15	1.798	50	47.73
70D20R10B (blended fuel)	832.58	40.84	2.850	-	41.6
N-butanol	815.27	33.1	2.266	17	-
Rapeseed oil	924.05	37.1	3.148	39.6–44	-

RESULTS AND DISCUSSION

The data of fuel consumption, smoke amount and emission of particles measured for diesel engine are shown in following tables. In the Table 5 are shown results for the engine which worked on standard diesel as reference, firstly after run-in period (10 hours) at 40% load and secondly, in Table 6 are data after 70 hours of operation at 70% load.

Table 5. Fuel consumption, smoke and emissions production after 10 hours run-in period – standard diesel

Engine speed	Output power	CO	CO_2	HC	NO	Smoke	Fuel consumption
min^{-1}	W	$g\ h^{-1}$	$g\ h^{-1}$	$g\ h^{-1}$	$g\ h^{-1}$	$g\ h^{-1}$	$g\ h^{-1}$
3,122	0	16.79	938.53	0.50	2.70	0.07	456.46
3,114	656	22.82	1,208.96	0.27	4.55	0.08	562.07
3,082	1,308	12.29	1,428.45	0.43	7.04	0.08	675.00
3,052	1,929	9.73	1,682.21	0.40	10.03	0.09	789.91
3,011	2,570	9.60	1,963.60	0.28	13.78	0.12	897.31
2,994	3,143	9.55	2,275.05	0.26	16.68	0.23	1,015.23
2,980	3,702	9.50	2,637.92	0.28	19.52	0.37	1,191.75
2,967	4,339	12.09	3,159.30	0.34	22.97	0.77	1,381.02

Table 6. Fuel consumption, smoke and emissions production after 70 hours of operation – standard diesel

Engine speed	Output power	CO	CO_2	HC	NO	Smoke	Fuel consumption
min^{-1}	W	$g\ h^{-1}$	$g\ h^{-1}$	$g\ h^{-1}$	$g\ h^{-1}$	$g\ h^{-1}$	$g\ h^{-1}$
3,123	0	42.32	977.95	1.13	1.45	0.08	477.05
3,111	638	40.46	1,188.13	0.91	3.04	0.09	568.47
3,093	1,249	36.98	1,397.60	0.75	5.55	0.10	671.40
3,072	1,937	31.84	1,663.45	0.74	9.02	0.13	787.52
3,052	2,579	29.19	1,949.42	0.65	12.38	0.16	913.10
3,015	3,162	25.47	2,228.18	0.70	15.48	0.25	1,045.08
2,934	3,715	25.73	2,499.36	0.64	19.19	0.30	1,174.55
2,914	4,304	30.20	2,973.24	0.63	21.70	0.90	1,357.49

Table 7. Fuel consumption, smoke and emissions production after 10 hours run-in period – blended fuel

Engine speed	Output power	CO	CO_2	HC	NO	Smoke	Fuel consumption
min^{-1}	W	$g\ h^{-1}$	$g\ h^{-1}$	$g\ h^{-1}$	$g\ h^{-1}$	$g\ h^{-1}$	$g\ h^{-1}$
3,226	0	33.43	1,010.11	0.72	1.99	0.08	516.97
3,211	658	28.15	1,265.14	0.77	3.91	0.09	629.64
3,197	1,299	22.94	1,521.52	0.72	6.59	0.11	740.99
3,179	1,932	19.23	1,792.05	0.70	9.91	0.14	867.78
3,157	2,578	15.10	2,096.07	0.54	13.57	0.09	1,005.14
3,137	3,174	15.00	2,425.10	0.60	17.17	0.17	1,159.69
3,127	3,754	14.96	2,805.45	0.56	20.96	0.22	1,328.63
3,120	4,405	20.81	3,321.34	0.83	23.63	0.48	1,546.09

The same data for the engine operated on blended fuel are given in Table 7 after run-in period (10 hours) at 40% load and in Table 8 after 70 hours at 70% load. Consequently, data are compared and commented.

Data were evaluated separately for the generator which worked on standard diesel fuel and for generator which worked on blended fuel.

Table 8. Fuel consumption, smoke and emissions production after 70 hours of operation – blended fuel

Engine speed	Output power	CO	CO_2	HC	NO	Smoke	Fuel consumption
min^{-1}	W	$g\ h^{-1}$	$g\ h^{-1}$	$g\ h^{-1}$	$g\ h^{-1}$	$g\ h^{-1}$	$g\ h^{-1}$
3,205	0	43.44	1,003.67	1.16	1.48	0.13	544.36
3,199	645	41.60	1,221.81	0.93	3.13	0.16	673.88
3,189	1,264	38.14	1,441.31	0.78	5.72	0.19	766.36
3,177	1,956	32.93	1,720.34	0.77	9.33	0.25	871.85
3,161	2,600	30.24	2,019.40	0.67	12.83	0.30	1,014.27
3,142	3,195	26.53	2,321.63	0.73	16.13	0.45	1,150.39
3,102	3,777	27.20	2,642.23	0.68	20.29	0.58	1,299.85
3,081	4,408	31.92	3,143.43	0.67	22.94	1.25	1,508.15

Generator operating on standard diesel fuel

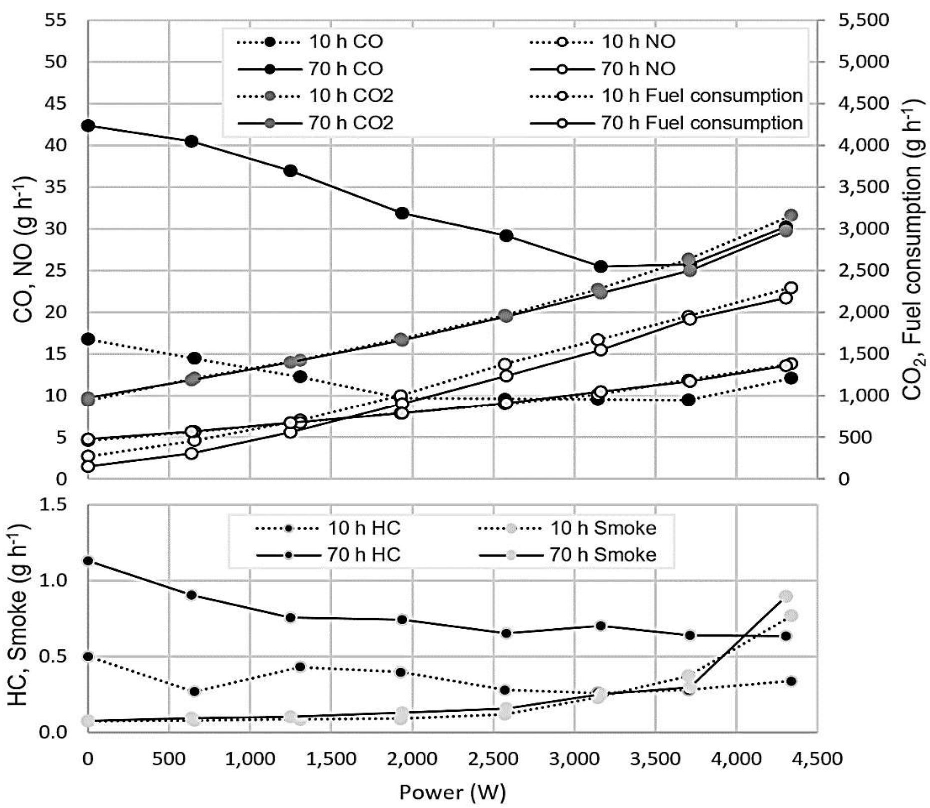

Figure 2. Hourly production - fuel consumption and emissions for the generator operated on standard diesel fuel after 10 and 70 hours of operation.

Considering the fact, that measured points were set with an error of less than 0.05% for revolutions and 0.8% for loads, the operating parameters of the generator were compared in hourly fuel consumption and emissions.

Fig. 2 shows the dependance of fuel consumption and emissions on the power that is taken from the generator as the energy output (used for external heating). Fig. 2 shows the dependance for the engine after run-in period (10 h) and after 70 hours of operation (70 h). It is evident from Fig. 2 that an increasing trend occurs mainly in the production of CO and HC and this progress has a negative effect on environment.

The increase of smoke amount and the production of particles for engine operating on standard diesel, is also confirmed in Fig. 3, where it is seen that the number of particles in the operation of the generator after 70 hours is higher in almost all the components of the spectrum than after 10 hours. Fig. 3 shows the number of particles in three different stages of the engine: the load-free (0%), the long-term load (70%) and the load close to the maximum (95%). The X-axis defines particle size in micrometres.

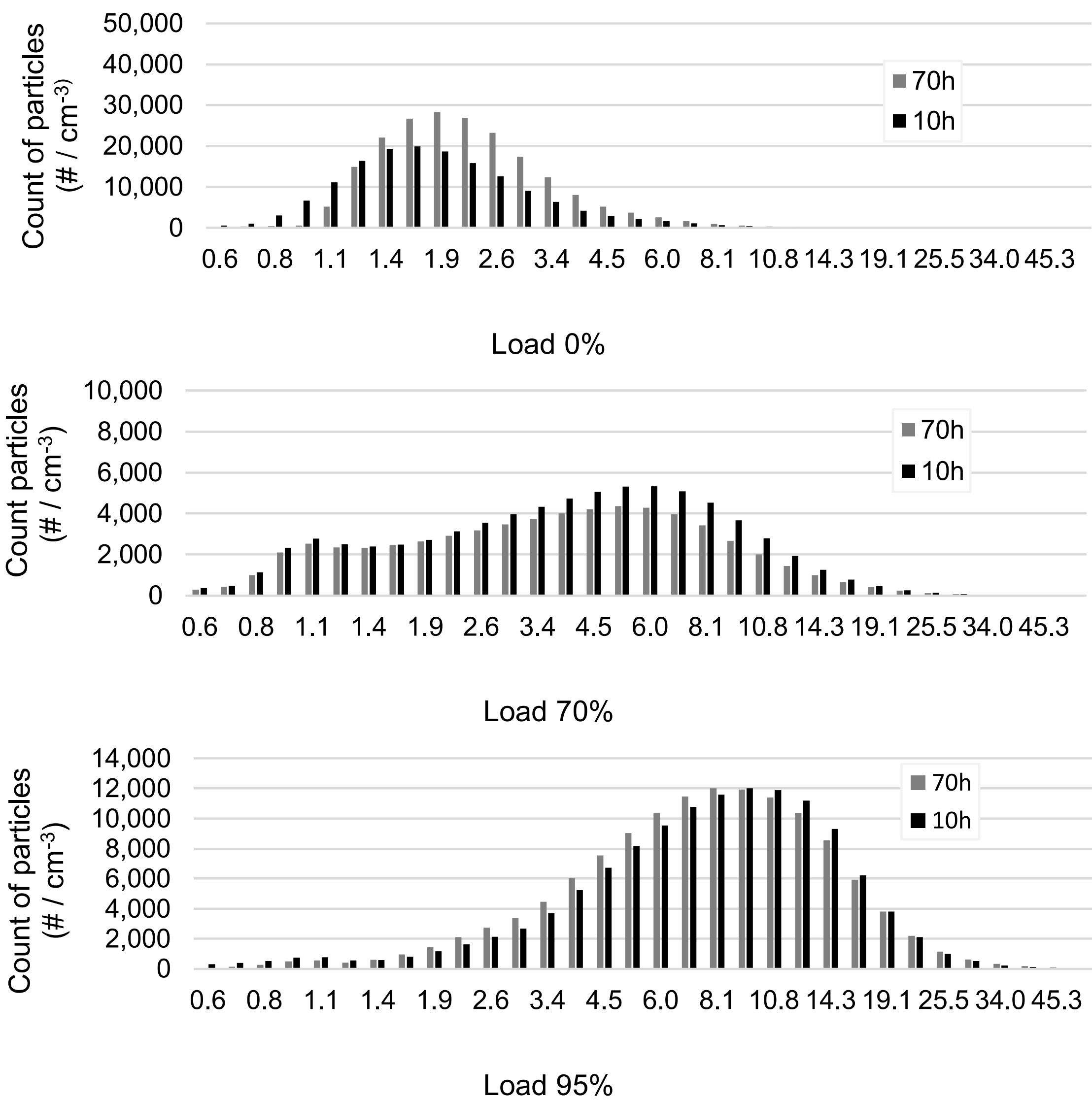

Figure 3. Exhaust particle distribution by its size (X-axis) – engine operating on standard diesel.

Overall, there has been an increase in production of emissions, especially for the components of CO and HC (those are the components where the measuring instrument is the least sensitive). As a result, the smoke increase is almost 15%. The unchanged fuel consumption is positive result – no significant increasing has been recorded.

The average changes are shown in Fig. 4. Here the average emission values and fuel consumption for the operation of generator are compared after 10 and 70 hours. It is obviocorrus that CO emissions have been increased 2.5 times and that the production of HC emissions has increased 2.3 times. Smoke in 15%. On the other hand, CO_2 emissions have decreased by about 2% and NO emissions by about 17%. Fuel consumption increased by only 1%.

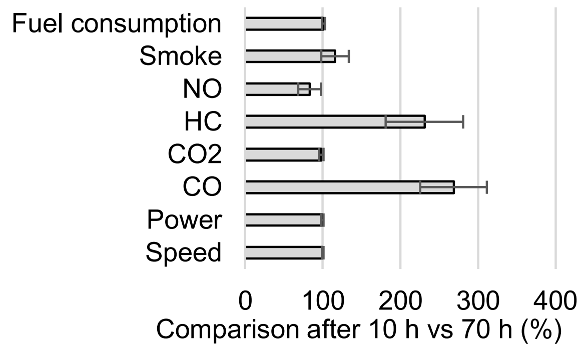

Figure 4. Change in emissions and fuel consumption in percent - 10 vs 70 h (diesel).

Generator operating on blended fuel

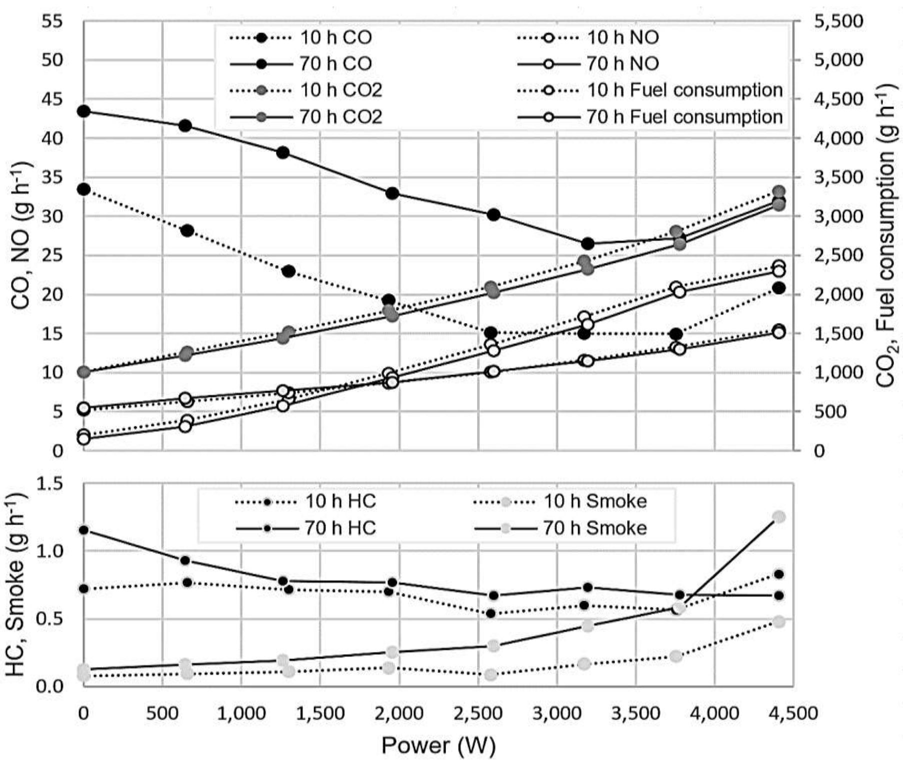

Figure 5. Hourly production - fuel consumption and emissions for the generator operated on blended fuel after 10 and 70 hours of operation.

Considering the fact, that measured points were set with an error of less than 0.4% for revolutions and 0.2% for loads, the operating parameters of the generator were compared in hourly fuel consumption and emissions.

Fig. 5 shows the dependance of fuel consumption and emissions on the power that is taken from the generator as the energy output (used for external heating). Fig. 5 shows the dependence for the engine after run-in period (10 h) and after 70 hours of operation (70 h). From Fig. 5 is significantly visible that an increasing trend occurs mainly in the production of smoke, CO and HC and this progress has negative environmental effect.

The increasing trend of smoke and the production of particles, is also confirmed by Fig. 6, where it is visible that the number of particles in the operation of the generator for 70 hours is mainly in the area of larger particles. Fig. 6 shows the number of particles only for three different states of the engine operated on blended fuel: the load-free motor (0%), the long-term load (70%) and the load close to the maximum (95%). The X-axis defines particle size in micrometres (μm).

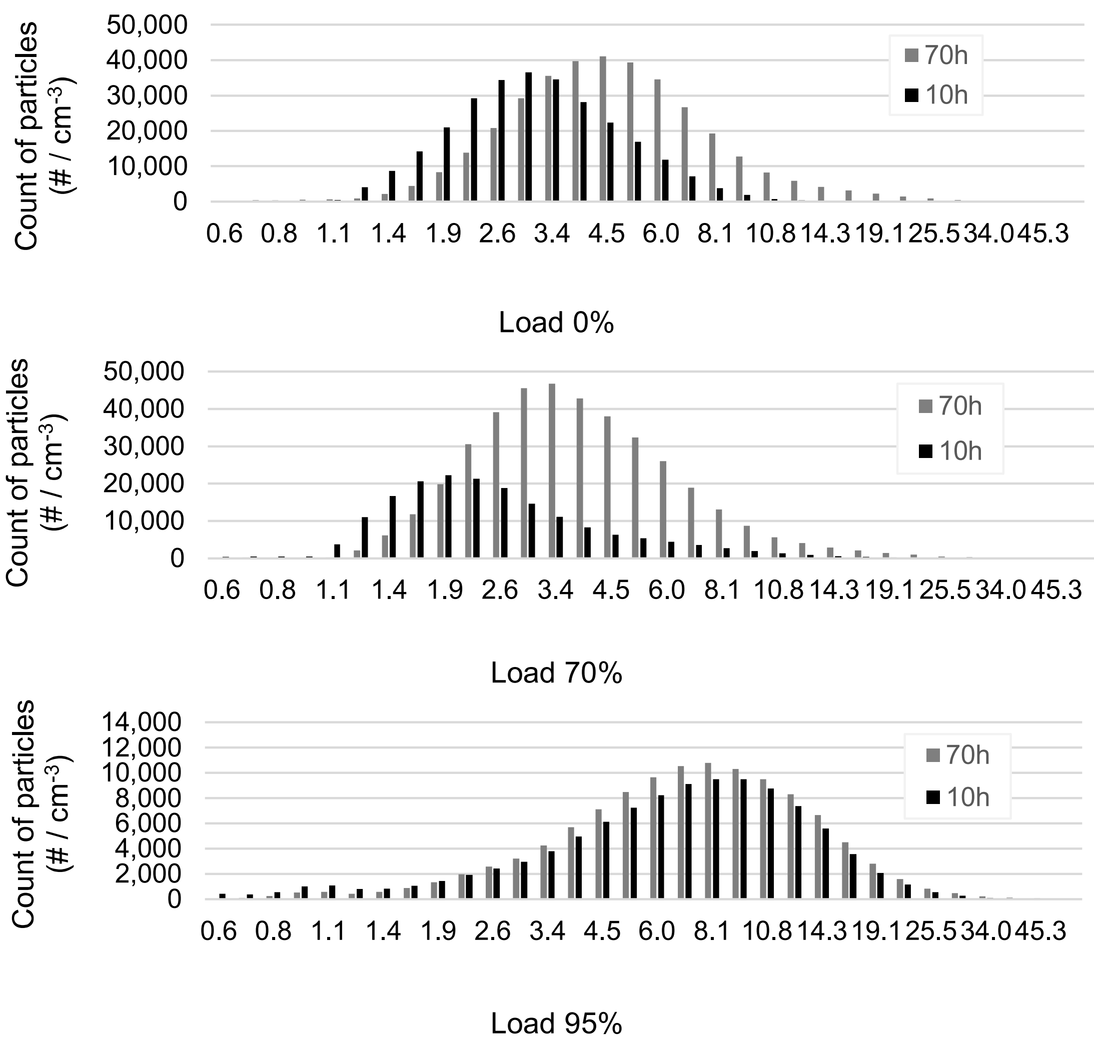

Figure 6. Exhaust particle distribution by its size (X-axis) - blended fuel.

As a result of this part of experiment, there has been an increase in production of emissions, especially for the components of CO and HC (those are the components where the measuring instrument is the least sensitive. As a result, the smoke increase is almost 130%. The unchanged fuel consumption is a positive result for this experiment.

On average, the changes for engine operated on blended fuel are shown in Fig. 7.

Here are shown average emission values and fuel consumption for the generator are compared after 10 and 70 hours. It is obvious, that CO emissions have been increased 1.6 times and increased HC emissions by 1.2 times. Smoke increased about 130%. On the other hand, CO_2 emissions have dropped by about 4% and NO emissions decreased about 10%. Fuel consumption increased only by 1%.

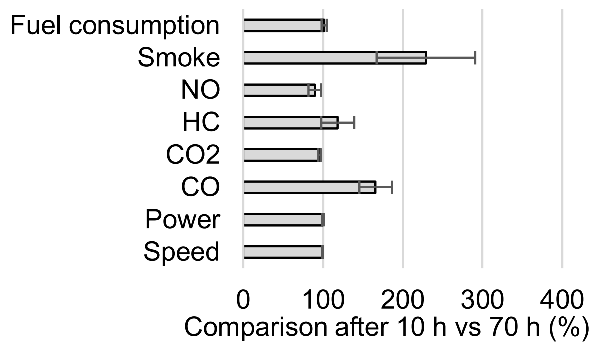

Figure 7. Change in emissions and fuel consumption in percent - 10 vs 70 h (blended fuel).

Comparison of generator operating on standard diesel and generator operating on blended fuel

Figs 8 and 9 show a comparison of the generators operated on standard diesel and blended fuel. The comparison is based on specific emissions and fuel consumption. The difference is then expressed as a percentage of all measured points. The displayed standard deviation shows how the components fluctuated at the measuring points.

Fig. 8 shows a run-in comparison of generators after 10 hours. In this graph is shown that the generator with blended fuel has higher CO and HC outputs, and at a higher load points there was a relatively significant smoke reduction of more than 20%. For other operating parameters, the difference is very low.

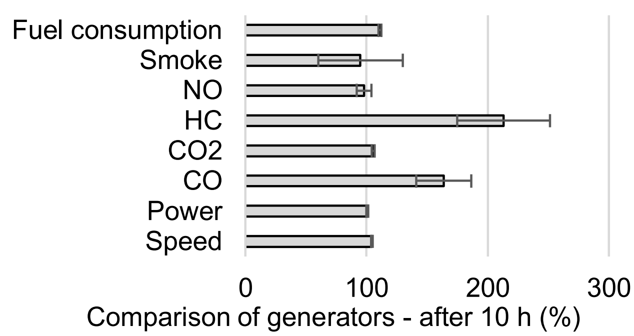

Figure 8. Comparison of the generator operated on blended fuel with the generator operated on diesel fuel after 10 h.

Fig. 9 shows the comparison of engines after 70 hours. When compared after 70 hours, almost all operating parameters appear to be almost same. The generator operated on blended fuel had slightly higher fuel consumption. Surprisingly, there was a noticeable increasing of smoke production, which was in average 75% worse than in generator operated on standard diesel.

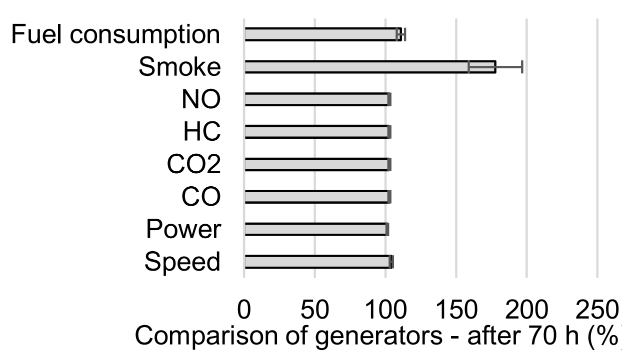

Figure 9. Comparison of the generator with blended fuel and generator with standard diesel - after 70 h.

CONCLUSIONS

During the long-term operation of diesel engines on standard diesel fuel and blended fuel, the generators were loaded with 70% of their nominal power using electric heaters. The operation parameters were measured in short-time measurements after run-in period and after 70 operating hours. The results after 70 operating hours shown that:

- After run-in period of the engines (10 h) it was shown, that blended fuel could have a positive effect on smoke, especially at higher loads (20% difference in results for smoke). After 70 hours, however, the opposite effect occurred. Smoke production of the generator operated on blended fuel increased by 75% in compare with reference diesel engine.
- The fuel consumption of the generator powered with blended fuel showed higher values, but these are caused by a lower calorific value of the blended fuel. Higher fuel consumption was observed both after 10 and 70 hours.
- From the point of view of particle production, it can be stated, that the diesel engine has comparable values after 10 and 70 hours of operation. On the other hand, the blended fuel generator has a significantly increased particle production after 70 hours, especially in higher particle sizes. When comparing these two generators, the production of particulates is clearly lower for the standard diesel-powered generator.

Lower emissions and smoke production using different biofuels and their diesel fuel blends can be achieved in short-time scale. In terms of long-term operation, however, they may cause operating difficulties in engines (cumulation of sediments, effect on oil content, etc.), which degrades engine operating parameters and may potentially result in increasing emissions and smoke production.

These results were achieved with specific composition of blended fuel containing 10% of n-butanol, 20% of rapeseed oil and 70% of diesel. Problems with emissions were most likely caused by vegetable (rapeseed) oil and its mechanical and chemical properties. Different mixtures might prove significantly different burning properties. Testing of various blended fuels will be object of future research projects.

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