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INVESTIGATIONS OF EXHAUST EMISSION OF BIOGAS SI ENGINE IN SEWAGE ELECTRIC GENERATOR PLANT

Tadeusz Borkowski

Maritime University of Szczecin – Department of Engineering
70-500 Szczecin, Waly Chrobrego 1-2
tel: +48 91 4809400, fax: +48 91 4809419
e-mail: tborkowski@am.szczecin.pl,

Abstract

The heat co-generation power arrangements in which SI reciprocating engines are fed with biogas can pose a real alternative of waste energy utilization in the cleaning processes of municipal sewage. The emission of exhaust gases in sewage plant vicinity is an unavoidable characteristic of this design, which raises the issue of appraising the harmful components of the gases. The study shows the results of experimental investigations conducted on three generator sets with modern SI reciprocating Deutz engines, TBG620V12K - type. The results of complete norm tests were applied in parametric calculation of final exhaust gas emission coefficients. Due to transitory lack of national legislation on exhaust gas emission in such applications, limit values of emission were adopted from TA-Luft (Germany).

Keywords: *SI reciprocating engine, exhaust emission, biogas, heat co-generation arrangement*

Introduction

Structural transformations in Poland together with transition to new economic system helped the process of growth of renewable sources of energy utilization. The development strategy for renewable energy establishes incremental share of renewables in fuel-energy balance, where the key source of energy will be the biomass. Notion of “biomass” includes the substances of vegetal or animal origin that undergo biodegradation and come from consumer products, miscellaneous waste and remnants of agricultural and forest production, and also industries reprocessing these products down the production chain. The realization of such definite aims and the development of renewable sources of energy create a possibility of maintaining energy independence, and also a pro-ecological modernization, diversification and decentralization of national energy sector [1].

The biogas constitutes an attractive source of comparatively cheap energy. The biogas installations can be fitted to existing sewage plants that serve towns and cities. The secretion of settlings from municipal sewages is an essential part of the purifying process. Sewer settlings display a large variability in chemical composition that is dependent on property of sewage, and the technology of purification and processing. The amount of settlings in municipal sewages after purification processes is estimated in the range of 0,5÷2,0 % of unpurified sewer waters volume. The anaerobic stabilization process of sewage settlings causes the formation of biogas as a side product. Growing requirements related to the degree of sewage purification, processing and neutralization of settlings, increase demand for heat input and energy consumption at sewage plants. The high-methane biogas may be used to cover energy demands of processes in biogas plants.

The biogas handling and its degree of utilization in heating up fermentation chambers plays a very important part in plant energy balance as only the surplus biogas can be made use of for other purposes as deemed appropriate. The demand for internal heat use in the process of biogas production relates to supporting the process of fermentation (heating up sewer settlings within range of 10÷35°C). Moreover, the neutralization of biogas through burning becomes an indispensable necessity in the aspect of preservation of natural environment, particularly the atmosphere, against the emission of un-burnt methane contained in biogas. It should be marked that the production of biogas is a side effect ensuing from the necessity of utilization of wastes in a least detrimental way for the environment.

The modern biogas installations, as a principle, should conclude with some type of energy production device. The biogas can be used in gas driven electric generators, gas boilers, heat co-generation arrangements that produce electric and thermal energy [2], [3]. The transmission of biogas for long distances is technically complex and therefore largely unprofitable. Its conversion to useable system gas is the most technologically advanced process of the utilization. The location of energy producing plants fed with biogas will therefore be in close proximity to municipal agglomerations. This calls for an assessment of their operational harmfulness mainly reflected in exhaust fumes emission. The aim of this work is an experimental appraisal of exhaust gas emission of engines operated in a modern sewage treatment plant of municipal sewage waters.

1. The biogas production installation – an analysis of feasibility of supplying SI engines with biogas

1.1. Biogas formation and composition

The mixture of gases that forms in biological processing of organic pulp, devoid of oxygen, is termed the biogas. This widespread in nature process can also be recreated in artificially altered conditions in reservoirs with organic pulp. The biogas forms as a result of anaerobic organic matter fermentation, for example biomass or sewer settlings, that is, biodegradable solid waste matter. The organic pulp transforms into biogas yielding also small amounts of heat and residual biomass. Created in this way mixture of gases consist mainly of methane and carbon dioxide. Small quantities of hydrogen, hydrogen sulfide and traces of ammonia and different vestigial gases, are not uncommon in the biogas. One of the methods of biogas production that can be applied in reference to bio-organic municipal wastes is anaerobic fermentation, which is held in three structural phases: hydrolysis, acid fermentation and methane fermentation. Participating in this process bacteria release the enzymes, which dissolve the material along biochemical reactions.

Subsequently, in the second structural phase, indirect products of these reactions decompose, with help of acid-forming bacteria, to fatty acids (acetic, butyric and propionic), hydrogen, and carbon dioxide. In the next structural phase, these products transform into substances preceding biogas formation. Methane forms in following, final phase as the result of wearing away of hydrogen. If all four phases take place in one fermentator, then this is defined as one stage process. However, dual module installations divide hydrolysis and acidification into two stages. The quantity and gas composition of emerging biogas depends on quality of output material and the quantity of organic compounds contained. The course of fermentation process is dependent on a sequence of factors of which the most important are: temperature (within range of 4÷70°C), time of reaction (at 30÷35°C it takes from 12 to 36 days, while at the temperature 52÷55°C, 12 last to 14 days) and the pH reaction (~ 7) [4].

The composition of the biogas is dependent on the chosen technological process and applied material, the universally occurring exhibits: 55÷85% CH_4, 14÷48% CO_2 with small quantities of: hydrogen sulfide, nitrogen, oxygen, hydrogen and other vestigial substances. The proportional share of methane in the biogas determines its calorific power. By means of example, biogas containing 65% methane has a calorific value of 23.0 MJ/m^3. Hydrogen sulfide, which is present in the biogas in small quantities, creates a number of technical problems [5].

1.2. Associated production of thermal and electric energy

The transformation of biogas energy into thermal energy occurs through combustion in boilers or SI engines. Due to the fact that calorific value of biogas significantly differs from universally applied natural gas, its use is not feasible with typical gas burners without prior modification, or SI engines with standard gas intake installations. The associated production of thermal and electric energy is realized through co-cogeneration system. A cogeneration unit consists of two elements: an electric system, which makes up the electric generator set (the SI engine - electric generator) and a thermal system. Electric energy is created thanks to the work of the generator set. Thermal energy, on another hand, is captured from heat exchangers built into piston engine installations: gas-air mixtures, lubricating oil, cooling water and exhaust gas.

The SI reciprocating engines are most often used in low power associated arrangements. The production of electric energy in associated arrangements from biogas requires large flexibility due to varied gas supply and unstable demand for energy. The possible occurrences of variation in gas flow or its composition during system operation greatly influence the installation design choice and the type of produced energy.

2. Project investigative foundations

2.1 Description of experimental test bench

The methane fermentation with biogas acquirement is conducted in closed fermentation chambers from where it is transmitted to a constant-pressure gas tank. During fermentation every one of four reservoirs of 5000m^3 capacity exudes biogas, with total volume of about 12000m^3 per day. Due to high concentration of hydrogen sulfide (~ 0.2%) the biogas is subjected to desulfurization until a value that meets PN-71/C-96001 standard is reached. The clearing of unpurified hydrogen sulfide takes place in a biological fluid reservoir of 60m^{3}capacity.

The biological desulfurization method relies on microbiological oxygenation of hydrogen sulfide by microorganisms of oxygenic bacteria on a biological bed. The purified gas has a concentration of hydrogen sulfide below 0.02g/m^3. Subsequently, the biogas gets accumulated in a wet type reservoir of 3000m^3 capacity in order to stabilize its flow in the supply installation, and be partially stored. The biogas is then pressed into supply system of two boilers rated 1400kW (each). Boilers are mainly used for heating up of fermentation settlings within spiral heat exchangers (technological water and fermentation settlings) up to 35÷37 centigrade Celsius, an indispensable value for realization of mesophillic fermentation. Whereas, the excess of produced gas is used for supplying the cogeneration arrangement that generates electric energy and heat. The layout of engine biogas supply installation is shown on Fig. 1. The source of the arrangement consists of SI gas engine propelling asynchronous generator, and a unit of two heat exchangers, which is shown on Fig. 2.

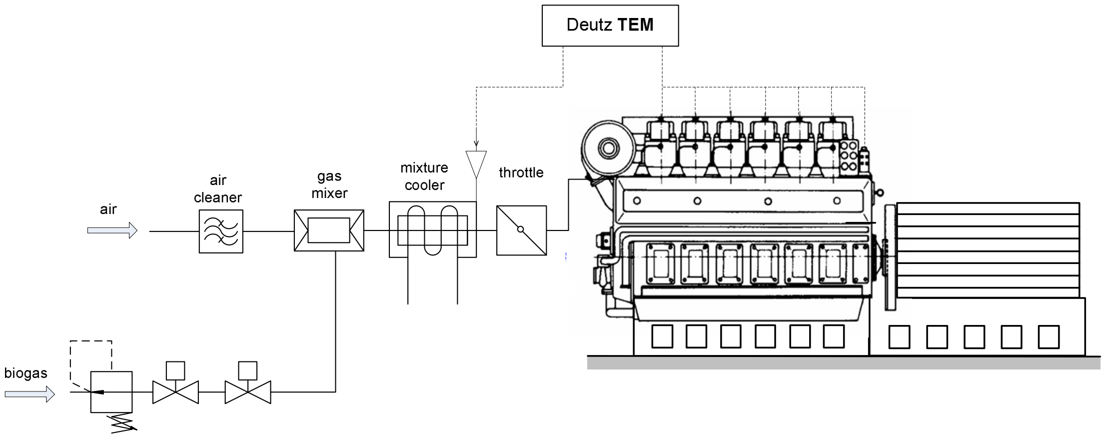

Fig. 1. Layout of generator set biogas supply system

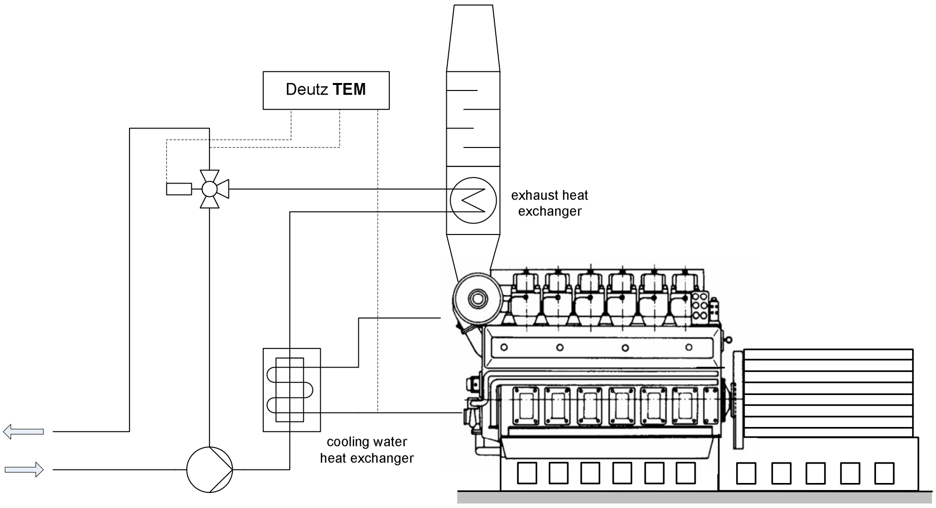

Fig. 2. Layout of generator set heat exchangers

This is a typical installation of associated power engineering CHP producing electric energy and heat, where the heat is delivered to a local distribution network. The produced electric energy largely covers plant energy demands. The production of biogas can provide heating for fermentation chambers, and supply generator set with gas also in the winter time. The biogas generator set is controlled by means of a control and monitoring system, and few automatic safety units, which cut off gas flow and arrest the engines.

2.2 The objective of investigation

The aim of the study is to assess the emission into plant surroundings of harmful gaseous exhaust components from engines in current-generating assembly at the sewage treatment plant. Standard exhaust emission coefficients were calculated and compared with the requirements of selected European standard (TA-Luft[1]) due to the lack of Polish environmental norm for this class of SI engines. The exhaust emission requirements and limits of TA-Luft do not belong to the lowest ones found in other European countries [6]. Experimental investigations were carried out during the site tests of generator units. The object of examination were three Deutz high speed engines, type TBG620V12K (12V- cylinders), whose basic parameters are presented in Table 1.

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[1] 30.07.2002 - Germany

Tab.1. Test engines specification

Effective power	kW	970
Nominal speed	1/min	1500
Bore/stroke	m	0.170/0.195
Mean effective pressure	bar	14.6
Specific fuel gas consumption[2]	kWh/kWh	2.53
Exhaust flow	kg/h	5114
Exhaust temperature (max)	°C	480
Thermal efficiency	%	48.7
Electrical efficiency	%	38.5
Total efficiency	%	87.2

2.3 The method of investigation

As stated earlier, the additional aim of this investigation was a comparison of obtained exhaust emission coefficients with TA-Luft standards. The realization of following engine exhaust gas measurements of harmful components was therefore essential: NO_x, CO, SO_2, and deflagrated hydrocarbons – measured in two ways: as the sum of all deflagrated hydrocarbons (THC - Total Hydrocarbons) together with a share of methane as NMHC (Non-Methan Hydrocarbons), that is hydrocarbons without the share of methane with the use of methane separating module - NMC. Exhaust emission in this context denotes the emission of the characteristic component of exhaust gas, expressed in [mg/m^3], related to standard conditions and constituting the result of averaging for the work of engine according to the standardized test cycle. The measurement of engine exhaust emission parameters and the methodology of calculations was based on definite principles of PN-EN ISO 8178 norm. The measurements were conducted according to the standard ISO 8178 (part 4) test cycle for engines operating with constant speed - D2. The engine exhaust gas emission components were quantified through volumetric measurement with utilization of recommended by ISO 8178 (part 1) norm exhaust gas analyzers (measuring arrangement assembly is shown on Fig. 3).

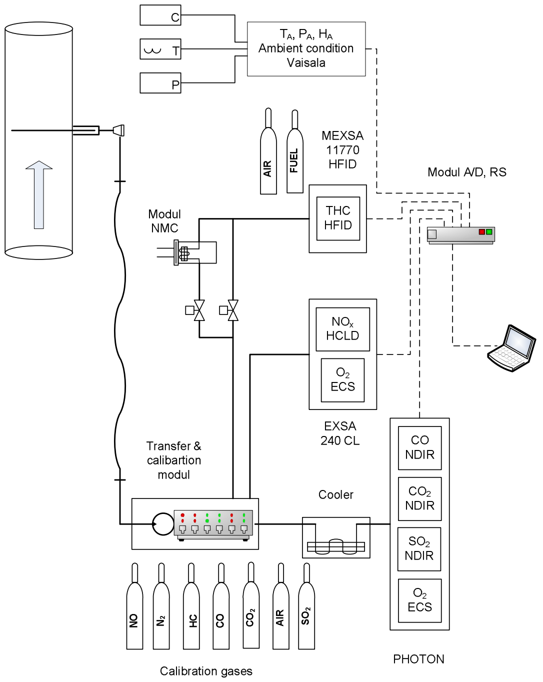

Fig. 3. Engine exhaust emission measurement setup

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[2] Fuel Gas Consumption/ Electric Energy

The exhaust gas analyzers were calibrated before commencing the measurements and audited upon finish. The samples of exhaust gas were continuously taken from pipe connector placed in exhaust gas duct (in funnel above the hall’s roof) of engine outlet system, after turbine and heat exchanger, by means of a heated line (192° C), all throughout test cycle duration. Observed exhaust gas component concentration values used in calculations, recorded at 1 second intervals, constitute the average value from three (one-minute) cycles of every structural constituent of test cycle program. The ambient surrounding conditions were registered with the use of an integrated device throughout measurements. Test engine parameters and indicators required for the test cycles and essential in determination of emission amount in accordance to ISO3046 (part I, II, III and IV) standard, were obtained through the registrations of engine control and supervision system.

The engines were supplied with gas fuel (biogas), proprieties shown in table 2. The fuel gas supply system was equipped with flow meters, pressure and temperature sensors, whose indications were used in assessment of fuel stream used by measurement apparatuses during the realization of engine test cycles.

Tab.2. Fuel gas specification

Factor			Value
1	Density @ 20°C	kg/m^3	1.095
2	Calorific value @ 20°C	MJ/m^3	19.74
3	CH_4	%	58.08
4	CO_2	%	34.97
5	N_2	%	3.82
6	H_2O	%	1.08
7	O	%	1.03
8	H_2S	ppm	>300

The majority of gas fuels being used to drive cogeneration arrangements is characterized by low calorific value. The usability of gas fuel in the aspect of CHP arrangements depends on a number of properties of which the most important are: calorific value, Wobbe number, knock combustion resistance, the speed of air-fuel mixture deflagration, and low content of impurities. The so-called methane number defines the knock resistance of the gas fuel. The higher the methane number is, the larger the knock resistance of the fuel. The gas fuel methane number corresponds to volumetric methane content in methane-hydrogen mixture. The value of gas fuel methane number depends on the content of methane and different hydrocarbons, and the share of inert gases such as CO_2 and N_2 [7]. The methane number drops with content growth of hydrocarbons other than methane. The low methane number raises the necessity of lowering engine compression ratio. The Wobbe number is the essential parameter characterizing gas usable properties in terms of utilization in energy-producing devices. It also defines the possibility of interchangeable application of various gas fuels. Its magnitude is equal in importance to gas calorific value and burning temperature.

In case of low-calorific gas deflagration, a deciding factor of fuel applicability in respective devices is its combustion velocity, which depends on air excess coefficient to combustion. It is accepted that the minimum combustion velocity of gas fuels in SI gas engines (without added mixtures of another flammable gas) is 0.008m/s. A number of the gas fuels applied in small engine-cogeneration arrangements are used independently, while some are enriched with natural gas.

3. The results of investigation

The emission coefficients calculations were based on representative group of data chosen from digital notation files of every test cycle load. Some examples of data used in analysis (example in Table 3 - appendix) are visually demonstrated on graphs: Fig. 4 for the generator set no:1, and Fig. 5 for the for the generator set no: 3. The statistical analysis of measurement data was executed for estimation of errors and value dispersion. The sample results of coefficients emission calculation is shown in Table 4 (appendix). The NO_x emission was corrected according to ISO standard procedure. The emission of chosen components of exhaust gas expressed as mass concentration converted to conventional conditions with the required 5% share of oxygen, allowed for emission comparison with TA-Luft norm.

A decision was made to enlarge the error margin on SO_2 measurement to account for measurement range of one of the sensors (0-5000ppm). The measured concentration value was within 10% of lower limit for a part of measurement duration. It should be assumed that resultant error could be as high as 15% of absolute value.

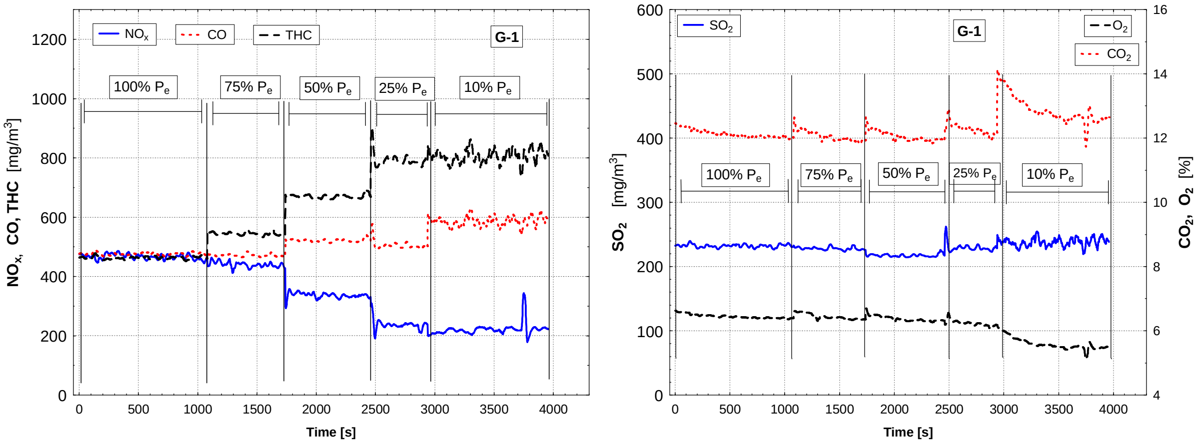

Fig. 4. NO_x, CO, THC, SO_2, CO_2 and O_2 concentration for generator set No:1 test cycle

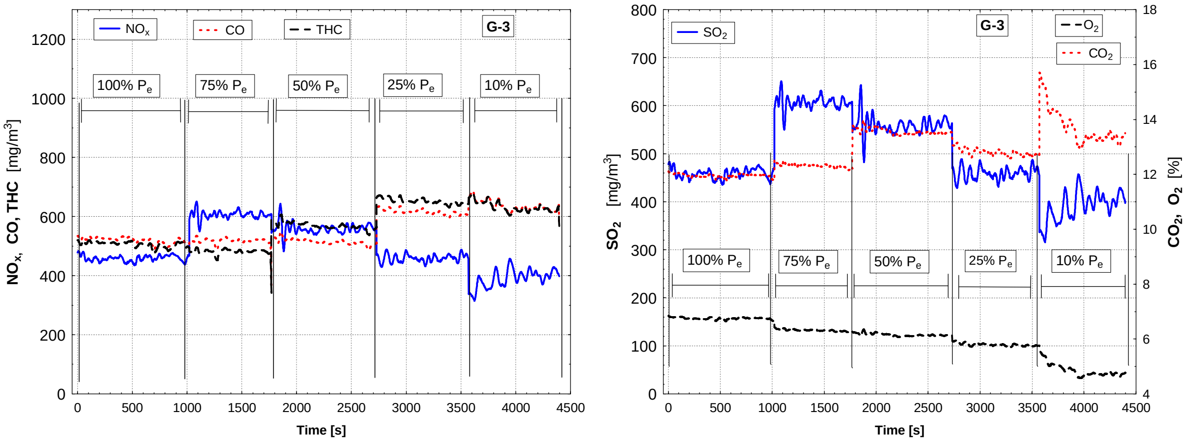

Fig. 5. NO_x, CO, THC, SO_2, CO_2 and O_2 concentration for generator set No:3 test cycle

This factor caused underestimation of SO_2 content in the exhaust gas. The inconsistency of the measured SO_2 concentration was confirmed with the qualitative content analysis of the biogas. However, it should be noted, the type - matter laboratory analysis of the biogas should not be treated as an absolute reference system for this particular setting, that is as fuel for the engines in question. Questionable methodology of gas sample uptake (plastic bags were used) was something of an issue, as well as assessment of H_2S presence only, omitting other biogas components that include sulfur. The measurement of all other exhaust gas emission components could be classified as highly accurate thanks to applied measuring devices (laboratory quality) and a fact of double measurements of NO_x and HC (two analyzers). The obtained concentration values of NO_x were closely compatible with the results of engine delivery-acceptance certificates, validating the methodology and apparatus accuracy. The THC measurement (Total Hydrocarbons, in Poland - Volatile Organic Compounds) was made in a dual form:

- the appraisal of total sum of hydrocarbons converted into pure carbon C according to effective reference methodologies in Poland.
- the appraisal applied to engines fed with biogas, that is NMHC (Non-Methane Hydrocarbons), according to TA-Luft requirements. The value of hydrocarbons sum was converted into pure carbon C, with subtracted value of methane - CH_4. This determination, like before, was realized through reference methodology.

4. Conclusions

The concord of mass emission of chosen components in exhaust gases of engines in question with TA –Luft norm can be defined in the following way:

1. In reference to NO_x emission, two engines, GS-1 and GS-2, showed full compatibility of emission factors in dominant range of engine effective load range. Small departure was noted, emission values surpassing the limit, for engines at nominal load as follow: for GS-1, it was 13.9mg/m^3 what constitutes a 2.8% breach of limit value; for GS-2, it was 37.5mg/m^3, what constitutes a 7.5% breach of limit value. Due to the methodology of test conduction at engine installation site and taking into account industrial setting and ensuing from it limited technical capabilities for conduction of measurements, both emission values satisfy limit conditions at 500mg/m^3 level within error range. However, the GS-3 engine demonstrated NO_x emission levels way above the limit, for both partial and nominal engine load. The maximal NO_x emission value for this engine was estimated at 661.3mg/m^3 at 75% effective load, which constitutes a violation of the limit by 32.3 %. It has been stated that NO_x emission of GS-3 engine was not compliant with requirements of TA-Luft norm.
2. All three engines showed CO emission levels below the limit of 1000mg/m^3, fulfilling the TA-Luft standard.
3. The SO_2 emission of all three engines showed values below the 350mg/m^3 limit, fulfilling the TA-Luft standard.
4. The NMHC emission of all three engines showed values below the 150mg/m^3 limit, fulfilling the TA-Luft standard.

The visual comparison of exhaust emission values specified in TA-Luft norm: NO_x (expressed as NO_2 concentration), CO, SO_2, NMHC for respective engines is shown in Figure 6, and 7 below.

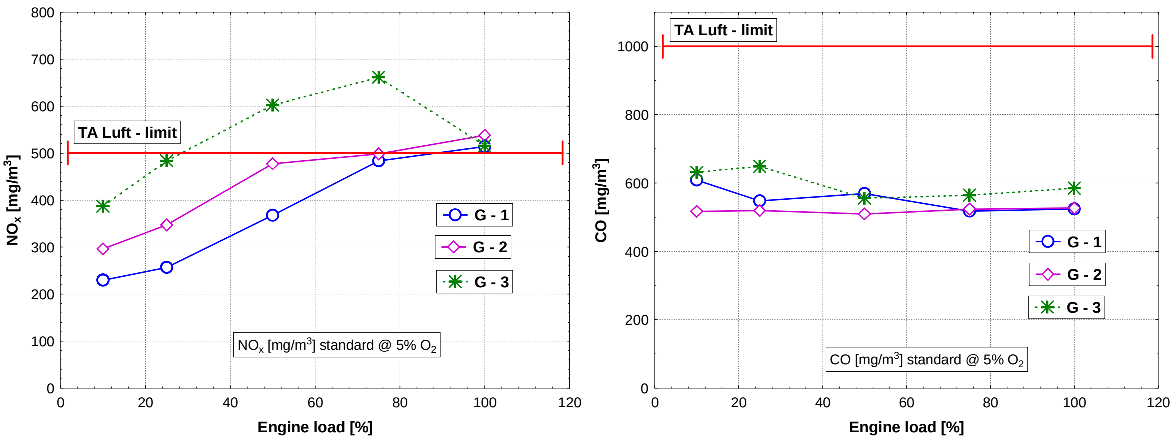

Fig. 6. Engine NO_x and CO emission values comparison against TA-Luft standards

Obtained engine NO_x emission factors could be classified as exceptionally low in comparison with adequate CI engines of corresponding power, whose NO_x emission is few times higher (weighted average specific emission coefficient). It should added that the NO emission coefficient for CI and SI reciprocating piston engines is subject to variation during operating period, as it is contingent on various factors, but it will be contained within the 10% range of absolute values reflecting engine effective load, and will remain at uniform level throughout the very long period of exploitation. It can only demonstrate considerable aberrations from the norm (growth or fall) in cases of engine damage (some functional units) or its technical modification.

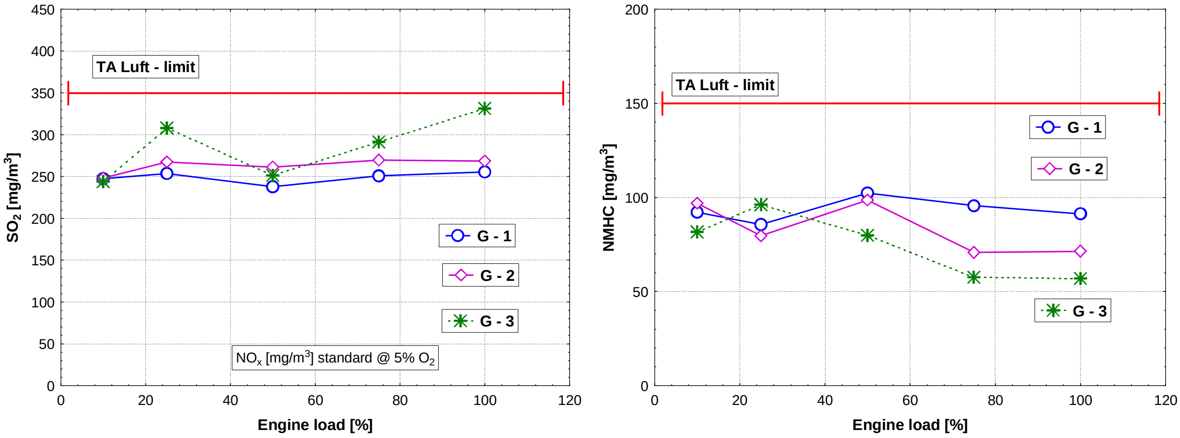

Fig. 7. Engine SO_2 and NMHC emission values compared against TA-Luft standards

In general terms, the exhaust emission performance of TBG620V12K Deutz engines can be described as correct and exceptionally low (in comparison to spontaneous ignition CI engines). The emission performance (except the GS-3 engine - the NO_x emission) is entirely in concord with TA-Luft requirements, and is very similar to modern engines of this class in analogous applications (fed with biogas). The exhaust gas component remaining in close relationship to fuel in use is SO_2, whose obtained concentration factors are burdened with relatively high uncertainty (the gas composition analysis and exhaust gas component concentration analysis). Those two reasons impinge upon the fact of accepting SO_2 emission in practice mainly relying on proven and accurate type - matter analysis of the fuel, but not on exhaust gas concentration analysis, which is less credible due to large underestimation in connection to present technology of quantitative assessment of this compound in the hot fumes.

Abbreviation

P_e	effective power,
n	rotational speed,
f_a	ambient conditions factor,
t_a	ambient air temperature,
t_c	charge air temperature,
t_b	biogas temperature,
t_g	exhaust gas temperature,
p_c	charge air pressure,
p_b	biogas pressure,
V_b	biogas flow,
w_g	exhaust gas velocity,
K_{HDIES}	Atmospheric air humidity correction coefficient for NO_x

Index
d – dry,
w – wet

Acknowledgments

The author would like to thank Budimex (Poznań) for the possibility of creating experimental part of this paper and the permission to use parts of this report in the study: Borkowski T., Zimnicki B.: Badania emisji spalin silników zespołów prądotwórczych typu TBG620V12K – Deutz, PPHU Atmoservice – Poznań, 2007

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Appendix

Tab.3. Engine test cycle data (example)

Object - parameter			Unit	Engine effective power				
				1	2	3	4	5
1	Engine	P_e	[%]	100	75	50	25	10
2		P_e	[kW]	970	727.5	485	242.5	97.0
3		n	[1/min]	1500	1500	1500	1500	1500
4		p_c	[bar]	1.75	1.15	0.57	0.03	0.01
5		t_c	[°C]	58.6	58.1	57.4	57.7	57.8
6	Ambient conditions	p_a	[kPa]	100.27	100.29	100.29	100.30	100.31
7		t_a	[°C]	30.7	32.6	32.9	33.0	28.9
8		H_a	[%]	34.0	30.0	29.0	34.0	27.9
9		f_a	[-]	1.045	1.055	1.057	1.057	1.036
10	Supply gas	V_b	$[m^3/h]$	411	325	228	145	83
11		t_b	[°C]	29.5	30.4	31.0	32.4	32.9
12		p_b	[kPa]]	81	82	82	85	85
13	Exhaust emission	t_g	[°C]	218	203	181	155	141
14		p_g	[Pa]	150	79	38	16	2
15		p_s	[Pa]	221	107	43	23	3
16		w_g	[m/s]	17.28	12.64	8.81	5.26	3.18
17		t_g	[°C]	167	164	121	124	108

18		O_{2s}	[%] vol	7.70	7.27	7.11	6.77	5.73
19		CO_{2d}	[%] vol	11.95	12.32	13.56	12.81	13.72
20		CO_d	[ppm] vol	417.33	415.0	412.5	430.3	509.4
21		SO_{2d}	[ppm] vol	103.0	93.5	81.5	89.3	86.1
22		THC_w	[ppm] vol	945.8	898.8	1064.0	1218.0	1183.3
23		NO_{xw}	[ppm] vol	228.2	300.1	276.2	213.4	200.3
24		K_{HDIES}	[-]	0.981	0.986	0.987	1.005	0.952
25		NO_{xcorr}	[ppm] vol	223.9	295.8	272.5	214.5	190.6
26		O_{2w}	[%] vol	6.75	6.3	6.15	5.80	4.85

Tab.4 Engine test cycle data (example)

Measurement number					**1**	**2**	**3**	
No:	Parameter			Unit	Value			Average
1	Ambient conditions	Barometric pressure		Pa	100520	100520	100520	100520
2		Air temperature		°C	30.5	30.6	30.6	30.6
3	Exhaust gas duct	Diameter		m	0.3			0.3
4		Surface area		m^2	0.071			0.071
5	Exhaust gas	Temperature		K	434.2	434.2	434.2	434.2
6		Static pressure		Pa	233.0	233.0	233.0	233.0
7		Dynamic pressure		Pa	124.6	124.6	124.6	124.6
8		Gas moistness (water)		%	4.2	4.2	4.2	4.2
9		Gas average velocity		m/s	17.4	17.4	17.4	17.4
10		Chemical composition	O_2	%	6.5	6.4	6.4	6.5
11			CO_2	%	12.3	12.1	12.0	12.1
12		Wet gas density*		kg/m^3	0.82	0.82	0.82	0.82
13	Concentration	NO_x		mg/m3	471	466	464	467.0
14		CO		mg/m3	477	476	476	476.3
15		SO_2		mg/m3	233	232	232	232.3
16		THC		mg/m3	464	463	463	463.3
17		NMHC		mg/m3	83	83	83	83.0
18	Emission	NO_x		kg/h				1.258
19		CO		kg/h				1.283
20		SO_2		kg/h				0.626
21		THC		kg/h				1.248
22		NMHC		kg/h				0.224

* measurement conditions