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Some aspects of long-term testing of cogeneration set fueled with biogas

Article presents the results of long-term testing of prototype of 64 kVA biogas cogeneration set (CHP – Combined Heat and Power), build with support of financial means from the MCP R&D program 1 2 1. Between others, the impact of fueling with biogas from the sewage treatment plant on the engine oil has been investigated. Used oil analyses unveiled adverse presence of silicon compounds, i.e. siloxanes, permissible level of which (according to MAN standard) was exceeded several times. In order to reduce these compounds, prototype biogas filter based on activated carbon has been developed. Based on initial calculations, overall efficiency of this cogeneration set is circa 70%. For the consumer needs, the entire installation is enclosed in a compact soundproof canopy. Besides environmental merits, the cogeneration set shows also economical advantages. If operating continuously, the gen-set *CHP would produce electrical and heat power in an amount that its purchasing cost would be returned after about 12 months, under condition of having biogas.*

Key words*: gas engine, siloxanes, cogeneration set (CHP), bio-mass, biogas*

1. Introduction

Gen-sets are independent machines generating electrical energy. Principles of their operation is based mainly on transformation of mechanical energy into electrical energy. It is done by an alternator coupled with a combustion piston engine, as a prime mover. Thermal energy created in result of fuel burning in the engine is transformed into mechanical energy in a form of crankshaft torque. Unfortunately, most of the energy from the fuel is lost with exhaust gases and into cooling system, and only 1/3 of it is transformed into mechanical work. Current combustion engine designs achieve overall efficiency not exceeding 40%, while efficiency of alternators coupled with them is in a level of 90%. The problem to increase the share of usable energy from the fuel transferred to the receiver (alternator) is an object of continuous improvements of combustion engines from the beginning of their history. From the technical point of view, small overall dimensions, compactness, portability and quick access to power source, substantially affected their popularity. Gen-sets with internal combustion engines have been used as stand-by power sources for hospitals and industry, as well as power sources in location with no power grid. This way, the history of technological progress, continuous improvements, innovations, discoveries and inventions, combined two branches of development: combustion engine and alternating current.

The principle of operation of the modern gen-sets is same as 100 years ego. During that time period, combustion engines underwent countless modernizations, in order to improve their efficiency and outputs. Nowadays, the necessity to protect environment as well as European Union's regulations on renewable energy sources, not only force but also financially support the use of alternative fuels [4]. Especially gaseous fuels coming from biomass – biogases are subject of interest. Tracking the current alternative fuel market, great interest in such fuels can be noticed within last few years, as never before. Attention is paid even to growing special varieties of plants (e.g. corn), producing new hydrolytic enzymes and highly efficient methane bacteria [5]. All these in order to improve efficiency and quality of the biogas.

Although the concept to recover thermal energy in generating sets is not a new idea and it was practiced as soon as at the end of XIX-th century, nowadays there is great interest in such type of cogeneration sets especially supplied with fuels from renewable sources. It is caused by introduction of EU directives and national laws related with energy policy. Particular attention is paid to support also small cogenerations (several dozen kW) and micro-cogenerations (up to 5 kW). The world biggest cogeneration economies are Denmark, Holland and Finland. It is worthy to underline that 82% of energy produced in Finland in 2012 came from cogeneration [8].

New regulations (Official Journal of 2018, item 1276) came into force in Poland in 2018, which promote installations producing electrical energy only from: 1) agriculture biogas, 2) biogas from landfills, 3) biogas from sewage treatment plants, 4) biogas others then listed in points 1–3 [3].

Rich literature on the use of cogeneration (especially from the last 10 years) confirms current trends at the energy market. It is obviously impossible to describe all the issues raised in the publications, but there are some aspects frequently touched by the authors. Attention is focused starting from the correct and optimal choice of power of the CHP set for given object requirements [9–12], up to calculations and economic analyses of the investments done [13–17]. Generally, looking at the cogeneration issues from the CHP sets operation modes point of view (stand-by operation and continuous operation), someone could tell these systems are easy to control and maintain. Review of the literature and own experiences show that such statements is wrong. Although I found no report where cogeneration sets made economic losses and their purchase was unprofitable, however to do so, the investor must obey the maintenance schedule and earnestly perform preventive maintenances (oil, spark plugs change, etc.). This in turn allows to avoid high repair costs and shut downs. Only this way high rate of the set operation time (availability) could be achieved, what also lead to economic profits. The literature mentioned above describes a set, for which its availability within 3-year operation period has been calculated at circa 95%. It proves very intensive and failure free operation. At such performance, investments could return as soon as within 2–

3 years. A separate issue, but related with cogeneration, is biogas production process and care to fuel the set with biogas free form harmful components. This is also fundamental for correct and reliable CHP sets operation [1, 18].

Considering the appearing market demand and current environmental trends, Sumera Motor developed cogeneration set (CHP) of 64 kVA fueled with biogas. Apart from electrical energy, the CHP provides also thermal energy recovered from cooling and exhaust systems. Water is a carrier of this energy. The CHP control system enables both parallel operation with mains as well as island operation. As of now this CHP is installed in the sewage treatment plant in Andrychów and operates continuously for about 5500 hours. Electrical energy is used for the plant current needs, and thermal energy for heating the rooms during winter time and to maintain constant temperature of one of the settlers.

Ensuring proper biogas parameters is essential for stable operation of the engine and the entire CHP. According to the engine manufacturer methane content in biogas should be minimum 55%. It should be desulfurized and dehydrated. Also pressure and flow capacity of the gas system is essential. Moreover, biogas from sewage treatment plants consists silicon compounds, so called siloxanes. They tend to settle on combustion chamber surfaces and penetrate into the engine oil, grinding off all the sliding surfaces, like bearing shells, what leads to accelerated engine parts wear out. Therefore, biogas needs to be cleaned from silicone compounds.

This article presents some aspects of long-term operation of CHP fueled with biogas from the sewage treatment plant. Between others, it presents the own-design biogas filter and its influence on siloxane presence in engine oil.

2. Cogeneration set CHP construction and general assumptions

Cogeneration set (CHP) of 64 kVA has been developed within the project RPMP.01.02.01-IP.01-12-038/16 („*R&D works related with development of a new cogeneration gensets fueled with biogas of 25 kVA, 32 kVA, 64 kVA planned to be implemented by Sumera Motor”*). This gen-set is based on Lovol's 1006-G6TAG13 gas engine and Linz Electric's PRO22S B/4 alternator (parameters presented in Table 1 and 2).

Table 1. Lovol 1006-G6TAG13 parameters

Parameters	Unit	Value
No. of cylinders	–	6
Rated power	[kWe]	90
Speed	[rpm]	1500
Frequency	[Hz]	50
Thermal efficiency	[%]	33
Natural gas consumption at 100% load	[Nm^3/h]	≤ 23.8
Max. gas pressure	[kPa]	~90
Engine oil capacity	[l]	16.1

Table 2. Linz Electric PRO22S B/4 parameters

Parameters	Unit	Value
Nominal power	[kVA]	75
Efficiency	[%]	90.3
Air volume	[m^3/min]	18

Apart from receiving electrical energy, thermal energy is also being recovered. It means the thermal energy that in conventional gen-set is lost via cooling system and exhaust system, here is being utilized. For this purpose, heat recovery installation has been made based on heat exchangers. Coolant/water and exhaust gases/water heat exchangers of suitable powers have been adopted. Water, which takes over the heat, flows through coolant/water heat exchanger and after initial heating up is directed to exhaust gases/water heat exchanger, where it is finally heated up. This hot water can be directly used by the user or used as next thermal energy carrier and directed to heat exchanger e.g. JAD type. Basic assumption when designing this system was to take out as much of heat from the coolant that the coolant/water heat exchanger would fully substitute the engine radiator. However, for practical reasons and as a protection the original engine radiator is kept in its place. In case of sudden coolant temperature increase above the max. allowable limit, temperature sensor sends signal to 3-way valve to open it and direct coolant to the radiator. When the coolant temperature drops down, 3-way valve closes and the heat exchange process comes back to previous circuit. Figure 1 presents the principles of operation of the heat recovery system.

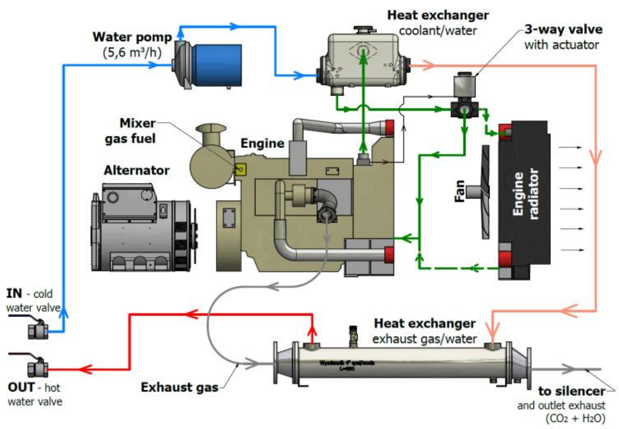

Fig. 1. Operation of the heat recovery system

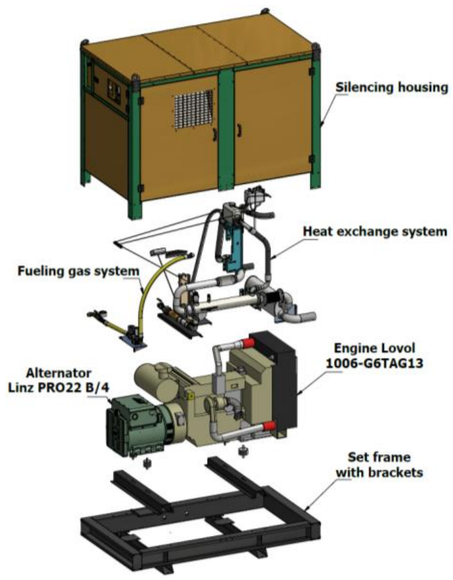

Fig. 2. Construction of the CHP 64 [kVA]

For the consumer needs, the entire installation is enclosed in a compact soundproof canopy. Figures 2 and 3 present the gen-set construction and actual photo.

Fig. 3. Side-view photo of the cogeneration set CHP 64 kVA

3. General assumptions and calculation of efficiency of the entire system

To have general view on the energy balance, theoretical calculations of total efficiency have been done. Starting point was the methane content in biogas from the sewage treatment plant and approximate energy balance for the engine used. With the NANOSENS instrument DP-27 BIO we determined 60% methane and 34% carbon dioxide content. Based on the information from the engine manufacturer, literature and our own experience, we applied the energy balance for combustion engine – as in figure 4. This diagram shows the thermal energy used (lost) for engine cooling is equal the thermal energy converted by the engine into effective work. Theoretical calculations gave the total CHP efficiency in a level of 76%.

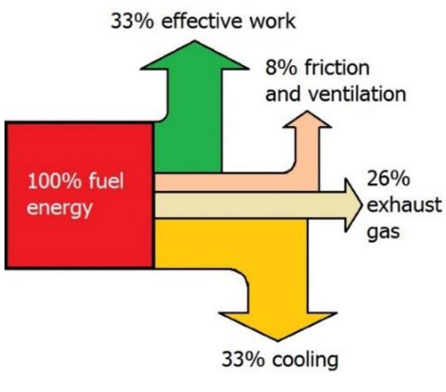

Fig. 4. Energy balance for biogas engine

For comparison, efficiency has been also determined in real operating conditions. For this purpose, the CHP has been equipped with the necessary sensors, heat meter and gas flow meter. The CHP has been loaded with 50 kW, and within half an hour heat, water inlet and outlet temperatures and gas consumption have been measured. Figure 5 shows control panel during measurements. Table 3 shows parameters measured and results of calculations of the actual efficiency of the entire system.

Fig. 5. Control panel during parameters reading. In the center, the main ComAp controller, below current water temperature readings at the heat exchangers. At the right – remote control module.

Table 3. Basic parameters related with gen-set efficiency under load of 50 kW

Parameter	Unit	Value
Calorific value of NG type E, W (according to PGNiG [6])	[MJ/m^3]	39,5
Biogas calorific value, Wg = 0.6·W	[MJ/m^3]	24
Gas consumption, U_g	[m^3]	30.46
Used gas energy, $E_{zuż\ g}$	[MJ]	721.9
Gen-set power, P	[kW]	50.95
Electric energy, $E_{n\ el}$	[MJ]	183.42
Water specific heat, c_p	[J/(kg·K)]	4183
Water density, ρ	[10^3 kg/m^3]	0.988
Water flow, l	[kg/h]	5498.6
Temperature increase, $\Delta T = T_{wyj} - T_{wej}$	[ºC]	12
Thermal energy, $E_{n\ c}$	[MJ]	276.01
Total energy, $E = E_{n\ el} + E_{n\ c}$	[MJ]	459.43
Measured efficiency, η	**[%]**	**63.64**

Calculations have been done with the following formulas. Energy of the gas consumed by the engine $E_{zuż\ g}$ has been calculated from:

$$E_{zuż\ g} = U_g \cdot W_g \ [MJ] \tag{1}$$

where: U_g – gas consumption [m^3], W_g – biogas calorific value [MJ/m^3].

The electric energy $E_{n\ el}$:

$$E_{n\ el} = \frac{P*3600}{1000} \ [MJ] \tag{2}$$

where: P – power of cogeneration set [kW].

Thermal energy $E_{n\ c}$ recovered thanks to heat exchangers has been calculated from:

$$E_{n\ c} = \frac{l*(T_{wyj}-T_{wej})*c_p}{10^6} \ [MJ] \tag{3}$$

where: l – water flow [kg/h], T_{wyj} – water temperature at the heat exchange system outlet [K], T_{wej} – water temperature at the inlet [K], c_p – water specific heat [J/(kg·K)].

The following formula presents the total energy (electric and thermal):

$$E = E_{n\ el} + E_{n\ c} \ [MJ] \tag{4}$$

The total CHP efficiency η is:

$$\eta = \frac{100*E}{E_{zuż\ g}} \ [\%] \tag{5}$$

Total calculated efficiency was 76%, while the actual operating efficiency is 64%. This difference could be due to unprecise assumptions of various parameters for the theoretical model. Another cause could be also undervaluation of energy losses at each level of energy conversion in the calculation process. On the contrary, the actual CHP efficiency has been determined in specific conditions resulting from given time period. Input parameters of biogas, water as well as ambient conditions are variables in time and also could impact the final efficiency. Having the above in mind, we could state that applying cogeneration installation doubled the total system efficiency.

4. Engine oil testing

During the long-term CHP gen-set testing, also engine oil has been tested to determine impact of biogas fueling on oil contamination and consumption. The key issue was to estimate the optimum oil change interval. Oil samples were taken every 300 operating hours to be sent for chemical analyses at the specialist laboratory of FUCHS OIL CORPORATION in Gliwice. First sample showed adverse content of siloxanes of 59.8 ppm, it means five times the allowable level (according to MAN the max. allowable siloxane level is 10 ppm). Siloxanes are chemical compounds present mainly in biogas from sewage treatment plants that result from anaerobic decomposition of substances commonly occurring in soaps and detergents. When burning biogas with siloxanes, silicon is released, which could react with oxygen or other gas components. Sediments with silicon dioxides or silicates (Si_xO_y) precipitate in result of such reactions. This sediment makes a layer of white substance of a few millimeters, tending to gather on combustion chamber (valves, pistons, cylinder liner), leading to accelerated engine wear out [1, 2, 7]. This way, silicon passes to oil, also grinding out the bearing shells, etc. Therefore, further oil testing became purposeful. At the same time, activities to reduce siloxane content in biogas has been undertaken, making activated carbon filter (Fig. 6).

Taking into account the gas flow, min. time of contact with carbon (~4 s), carbon density 0.5 kg/l, a batch of activated carbon of circa 33 [kg] has been calculated. After 300 hours of gen-set operation with filter, oil sample has been tested and silicon content was reduced 4 times from 79 to 19 ppm – Fig. 7. Next samples showed silicates reduction to the allowable limit 10 [ppm]. To obtain an overview how often the activated carbon should be replaced, its weight has been measure after a month of operation. The weight of 1 dm^3 was 551 [g]. One dm^3 of completely used activated carbon should weigh circa 0,7 [kg]. Taking the above into account, it has been decided to replace the activated carbon every 4 months of operation, and next oil samples testing every 500 hours. Fig. 8 presents weighting of the activated carbon.

Besides silicon compounds, some other metals were noticed in the engine oil samples, like copper, tin, lead and iron. The highest content was noticed in first three samples, when the gen-set did not even reach 1.000 working hours. Most likely it was related with reaching out of engine. After about 3000 hours of operation, content of tin and lead was almost zero.

a)
b)
c)

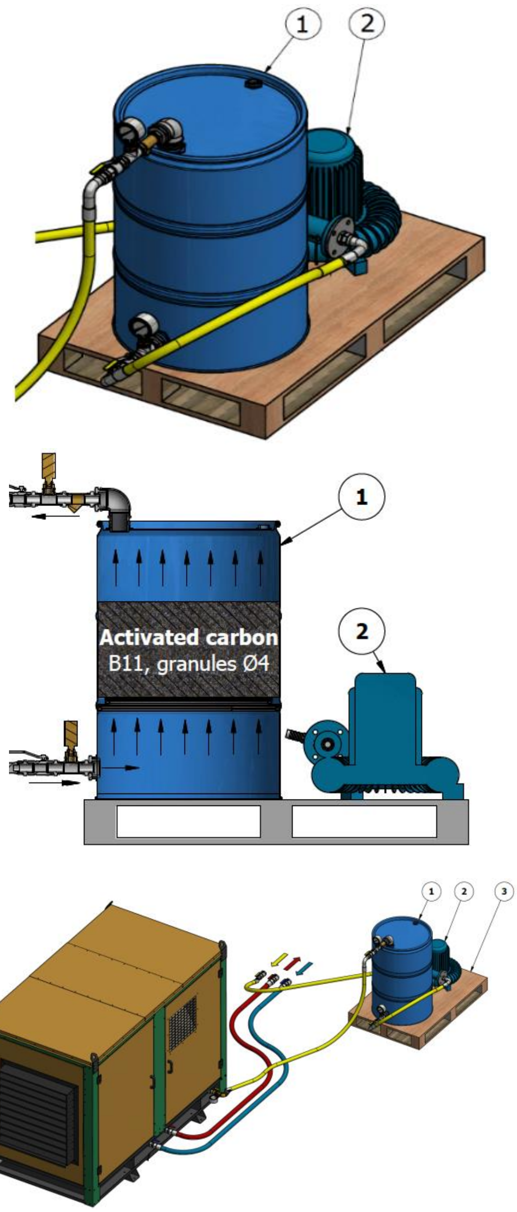

Fig. 6. Biogas filter with activated carbon, a) and b) – general view and intersection, c view of the entire installation. 1 – filter, 2 – biogas blower, 3 – euro pallet

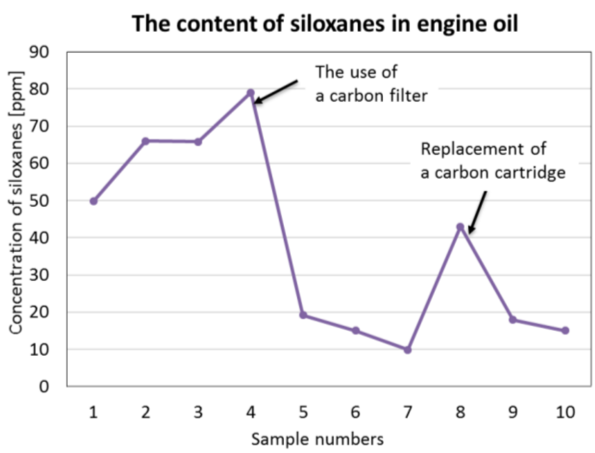

Fig. 7. Diagram presenting impact of activated carbon filter on siloxanes content in engine oil [FUCHS]

Fig. 8. Weighting of 1 l of activated carbon. Left side – clean carbon – 511 g, right side carbon after 4 months of operation – 650 g

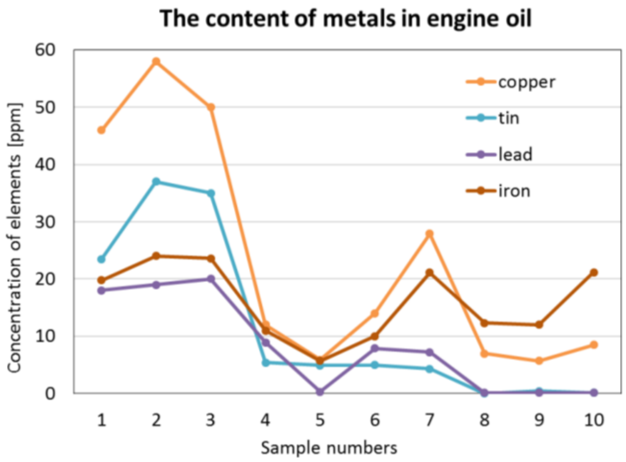

Fig. 9. Content of metals in engine oil samples [FUCHS]

Because all the other engine oil parameters, like kinematic viscosity, insoluble contamination content, soot and sulfur content and ph were for all the samples within the standard, it has been estimated the optimum oil change interval as 500 working hours (under condition of using FUCHS GANYMET ULTRA oil). It has been decided to replace the activated carbon every 2500 working hours, it means 3.5 moths of continuous cogeneration set CHP operation.

5. Conclusions

The following general conclusions have been drawn from our own observations. The cogeneration set CHP described herein:

- enables continuous supply of electrical and thermal energy (with breaks for maintenance: oil, coolant change, etc.),
- thanks to heat recovery, the total efficiency of CHP compared to the engine itself is doubled ,
- should operate as a stationary unit and requires continuous reception of thermal energy. It is, between others, because the engine radiator is substituted with coolant/water heat exchanger. Similarly, there is also exhaust gases/water heat exchanger. Due to high temperatures of exhaust gases, water in this exchanger should continuously circulate.
- at first start-up the water installation must be fully deaerated,
- will undergo further improvements. It seems to be reasonable to use combustion engine without mechanical fan and substitute it with electric fan, which would turn ON only in case of possible overheating. It would improve noise emission and total gen-set efficiency by circa 4 [%].

Moreover, the use of activated carbon filter in biogas installation enabled effective reduction of silicon compounds in engine oil, what allowed to increase the oil change interval from 300 to 500 hours of operation. Attention should be drawn that after replacing the used activated carbon with a new one, the gas installation needs to be blown out with biogas, in order to remove the air. This is to avoid troubles with gen-set restarting and possible explosion.

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Nomenclature

MCP R&D	Małopolska Enterpreneurship Center	CHP	combined heat and power

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