report

bioenergy2020+

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Test Report - Lean Gas Test

Operation of a Stirling engine with sewage gas

Date	19 September 2019
Number	925 TR N101340
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Project number	N101340 Schwachgas BHKW III
Project duration	1 October 2018 – 30 September 2019
Supported by	The Austrian Research Promotion Agency (FFG) in the FFG base programme: “Problemgas-BHKW”

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1. Introduction

In this report we present the test procedure and the results of a Stirling engine operated with sewage gas (lean gas) from the sewage plant in Schärding. The Stirling cogeneration unit was operated from July 15th, 2019 to August 13th, 2019. The Stirling cogeneration unit was installed on a trailer enabling mobile use. The connection for the sewage gas, the power connection and the heating connection were facilitated by pipes and cables between trailer and sewage plant. Figure 1 shows the installed trailer in front of the sewage plant.

Figure 1: Installed trailer at the sewage plant in Schärding.

The test presented in this report was conducted on the July 23rd, 2019 at the water-treatment association and sewage plant Schärding in Passauerstraße 33, 4780 Schärding.

It was conducted with a Stirling engine of the series alphagamma® G600i from Frauscher Thermal Motors GmbH in order to evaluate the technical specifications of the cogeneration unit in the operation with sewage gas. In particular these are the electrical efficiency factor and the emissions in the exhaust gas.

1.1 Emission thresholds of cogeneration units

Maximum emissions from the operation of cogeneration units are regulated on a national level. In Austria the Constitutional law *Art 15a B VG*[1] *“über das Inverkehrbringen von Kleinfeuerungen und die Überprüfung von Feuerungsanlagen und Blockheizkraftwerken”* is applied. The thresholds are presented in Table 1.

Regulation	**Fuel**	**Fuel heat capacity**	**CO [mg/m³]**	**NO_x [mg/m³]**	**NMHC**[2] **[mg/m³]**
Art. 15aB VG, 2013	natural gas, liquid gas	up to 2.5 MW	200	250	150
Art. 15aB VG, 2013	sewage gas, biogas, wood gas, landfill gas	up to 0.25 MW	1000	1000	-

Table 1: Austrian thresholds for cogeneration units. Emissions related to 5% residual oxygen in the exhaust gas.

As shown in Table 1, the thresholds for the operation of cogeneration units up to 0.25 MW with sewage gas and biogas are set at 1000 mg/m^3_{STP} related to 5% residual oxygen for carbon monoxide and nitrogen oxides.

In Germany the “Technische Anleitung zur Regelung der Luft (TA Luft)” for the introduction of cogeneration units and gas engines is applied. The thresholds in TA Luft[3] are presented in Table 2.

Regulation	**Fuel**	**Fuel heat capacity**	**CO [mg/m³]**	**NO_x [mg/m³]**	**CH_2O [mg/m³]**
TA Luft, 2002	natural gas	up to 50MW	300 (se.i + sp.i)	250 (other four stroke Otto)	60
TA Luft, 2002	biogas, sewage gas	up to 50MW	1000 (sp.i) <3MW	1000 (PI) <3MW, 500 (LGE, other four stroke Otto)	60

Table 2: German thresholds for combustion engines. Emissions related to 5% residual oxygen in the exhaust gas; se.i.=self-igniting, sp.i.=spark ignition, PI=pilot injection, LGE=lean gas engines)

[1] Source: Legal Information System of the Republic of Austria https://www.ris.bka.gv.at/GeltendeFassung.wxe?Abfrage=LrSbg&Gesetzesnummer=20000826

[2] NMHC = non-methane hydrocarbons

[3] Source: Federal Ministry fort he Environment, Nature Conservation and Nuclear Safety; https://www.bmu.de/fileadmin/Daten_BMU/Download_PDF/Luft/taluft.pdf

As shown in Table 2 in Germany the thresholds for carbon monoxide (CO) for spark igniting engines and for nitrogen oxides (NO_x) for pilot injection engines operated with biogas and sewage gas are set at 1000 mg/m^3_{STP} related to 5% residual oxygen. The thresholds for nitrogen oxides for lean gas engines and other four stroke Otto engines are 500 mg/m^3_{STP}. The threshold for formaldehyde (CH_2O) is 60 mg/m^3_{STP}.

According to the Federal Immission Control Act (4. BImSchV) the operation of cogeneration units up to 1 MW heat capacity do not require permissions. However, the used thresholds are seen as appropriate for state-of-the-art technology. Therefore it is suggested to comply with the thresholds presented in Table 2. Stirling engines should be oriented towards these thresholds[4].

[4] Source: Bernd Thomas: Mini-Blockheizkraftwerke. Vogel Buchverlag, 2011, S.86.

2. Material and Methods

2.1 Engine

The Stirling engine which operates according the alphagamma® procedure is a new development from Frauscher Thermal Motors GmbH and represents a combination of an alpha- and a gamma-machine. This novel concept combines the advantages of both technologies while disadvantages are minimized.

"alphagamma® technology reduces the work of the expansion piston by approximately half compared to the alpha type and by around 30% in comparison to the beta and gamma type. Both pistons perform positive work. Consequently, piston forces, piston friction, and the bearing load of the piston rod bearings and crankshaft main bearings are reduced. The new technology therefore provides the qualification of placing highest life expectancies on the roller bearings despite lubrication-free operation and achieving particularly high efficiencies due to minimal frictional forces."[5]

The surveyed engine oft he type G600i is specified as follows:

- Cubic capacity: 600 ccm
- Integrated generator in the buffer space

The test setup including the Stirling engine, a lean gas burner, an air preheater and a generator was established on a trailer. This trailer is shown in Figure 2.

[5] Frauscher Thermal Motors GmbH, Source: https://www.frauscher-motors.com/prototypen/alphagamma®-motoren.html

Figure 2: Measurement setup and Stirling cogeneration unit in the trailer

2.2 Experimental procedure

The Frauscher alphagamma® Stirling G600i was operated with sewage gas as fuel. The aim was to assess the operational reliability and the technical specifications at the so-called "lean gas operation". The sewage gas supply was provided from the sewage plant in Schärding. The composition of the sewage gas was not adjusted. During the test day several gas samples were taken for the analysis in the lab of BIOENERGY 2020+ GmbH.

The Stirling cogeneration unit was regulated according to the residual oxygen content in the exhaust gas which was measured by a lambda sensor in the moist gas. Due to variations of combustion air the residual oxygen content of the exhaust gas could be adjusted. This directly impacts emissions and efficiency. By the determination of two different operation points the impact of the oxygen on the power on the emissions should be analysed.

In addition to the measurements of oxygen with the lambda sensor in the moist exhaust gas also the emissions were determined with the analyzer Horiba PG350. This analyzer extracts a partial stream (exhaust gas sample) which is dried before the measurement. For the data evaluation of the emissions the oxygen content which was measured by the analyzer Horiba PG350 was used.

In order to assure low return flow temperatures for the operation of the Stirling engine, a second heat consumption device was installed. In addition to the heat sink in the sewage plant an air-water heat exchanger, which was installed on the trailer, was put into operation. The return flow temperature for the heating of the fermenter (heat sink of the sewage plant Schärding) would be too high for the efficient operation of the Stirling engine.

The evaluation period of the respective two phases accounted for one hour at stationary conditions. The first operation point was measured when the residual oxygen content in the exhaust gas was at 6.9%. The second operation point was measured at a residual oxygen content of 5.5%. During the first operation point a particle measurement with a Wöhler SM500 was conducted.

After the measurements of steady-state conditions a measurement at unsteady conditions was conducted. Therefor the oxygen content was adjusted in minute intervals in order to achieve typical curves of the emission values and of the electrical power related to the residual oxygen content in the exhaust gas as well as the operation temperature.

2.3 Evaluation method

For the assessment of the different powers and efficiency factors, the determination of the lower and the upper heating value of the sewage gas are decisive. The samples for the determination of the main compounds of the sewage gas were taken from the gas line directly before the gas meter in the trailer. Gas bags with a filling capacity of 4 liters were used. The samples were analyzed in the lab of BIOENERGY 2020+ GmbH. The composition of the dry exhaust gas is presented in Table 3.

Sample	Date	Time	Amount [l]	O_2 [%]	N_2 [%]	CH_4 [%]	CO_2 [%]	H_2S [%]	Sum [%]
1	23/07/2019	10:22	4	0.5	1.6	60.5	38.3	0.1	100.9
2	23/07/2019	10:25	4	0.1	0.3	61.6	39.0	0.1	100.9
3	23/07/2019	15:52	4	0.1	0.5	62.1	39.0	0.1	101.8
4	23/07/2019	15:55	4	0.1	0.3	61.3	39.1	0.1	100.9
Mean value (sample 2-4)				0.1	0.4	61.7	39.0	0.1	101.2
Mean value related to 100% (sample 2-4)				0.1	0.4	60.9	38.6	0.1	100.0

Table 3: Compositions of the sewage gas samples and calculation of a mean values.

Because the sum of measuring tolerance is slightly above 100%, the mean values were related to 100%. It is assumed that the higher oxygen content in sample 1 is a result of leak-problems during sampling, as it deviates clearly from the other samples. Consequently the samples 2 to 4 were used for the determination of the lower and the upper heating value in the lab.

During the test day the methane concentration were between 61.3% and 62.1%. The carbon dioxide concentration was between 39.0% and 39.1%.

Because of the long supply line and the subsequent gas control system in the trailer it is assumed that the raw gas was already dehumidified at the inlet to the burner.

The following parameters were determined for the two test evaluation phases:

- Gross power of the generator
- Lower heating value of the fuel (per m^3)
- Upper heating value of the fuel (per m^3)
- Efficiency (gross power and overall power related to the lower and the upper heating value respectively)
- Amount of gas and gas power
- Emissions (CO and NO_x related to 5% residual oxygen according to thresholds)

3. Evaluation and Discussion

3.1 Lower and upper heating value

The lower heating value (LHV) and the upper heating value (UHV) of the sewage gas were determined using the gas composition presented in Table 3. For the calculation the mean values of CH_4 and H_2S, related to 100%, were used resulting in the following fuel specifications:

- LHV: 6.08 kWh/m^3_{STP}
- UHV: 6.74 kWh/m^3_{STP}

3.2 Operation point 1: 6.9% O_2

The mean values of the test with stationary conditions on July 23rd, 2019 from 10:30 to 11:30 with a residual oxygen content of 6.9% in the dry exhaust are presented in Table 4.

Parameters	Value	Unit
Gas amount per hour*	3.22	m^3/h
Power of the gas burner related to the LHV	19.55	kW
Power of the gas burner related to the UHV	21.69	kW
Electrical power (generator-gross power)	6.04	kW
Overall cooling power	10.59	kW
Electrical efficiency (gross power to LHV)	30.9	%
Electrical efficiency (gross power to UHV)	27.9	%
Efficiency of the engine related to LHV	85.1	%
Efficiency of the engine related to UHV	76.7	%
CO	224	mg/m^3_{STP}, rel. to 5% O_2
NO_x	391	mg/m^3_{STP}, rel. to 5% O_2

***related to standard temperature and pressure**

Table 4: Evaluation of operation point 1

The efficiency of the engine was determined from the relation of the overall cooling power plus electrical power related to the respective heating value.

The particle measurement of 15 minutes during operation point 1 revealed a total dust concentration of 8 mg/m^3_{STP}, related to 5% O_2.

3.3 Operation point 2: 5.5% O_2

The mean values of the test with stationary conditions on July 23rd, 2019 from 12:15 to 13:15 with a residual oxygen content of 5.5% in the dry exhaust are presented in Table 4.

Parameters	**Value**	**Unit**
Gas amount per hour*	3.21	m^3/h
Power of the gas burner related to the LHV	19.49	kW
Power of the gas burner related to the UHV	21.62	kW
Electrical power (generator-gross power)	6.06	kW
Overall cooling power	10.67	kW
Electrical efficiency (gross power to LHV)	31.1	%
Electrical efficiency (gross power to UHV)	28.0	%
Efficiency of the engine related to LHV	85.9	%
Efficiency of the engine related to UHV	77.4	%
CO	306	mg/m^3_{STP}, rel. to 5% O_2
NO_x	497	mg/m^3_{STP}, rel. to 5% O_2

*****related to standard temperature and pressure

Table 5: Evaluation of operation point 2

The efficiency of the engine was determined from the relation of the overall cooling power plus electrical power related to the respective heating value.

3.4 Evaluation of a characteristic curve

During the unsteady measurement phase characteristic curves were determined which illustrate the relationship of carbon monoxide, nitrogen oxides and the electrical power with the residual oxygen content and the temperature of the process gas. In Figure 3 the curves of the emissions related to the residual oxygen content from this measurement phase are shown. Emission values which were measured in a second interval were calculated to the unit mg/m^3_{STP}, related to 5% residual oxygen content. It can be seen that both, carbon monoxide emissions and nitrogen oxide emissions, decrease with increasing residual oxygen content.

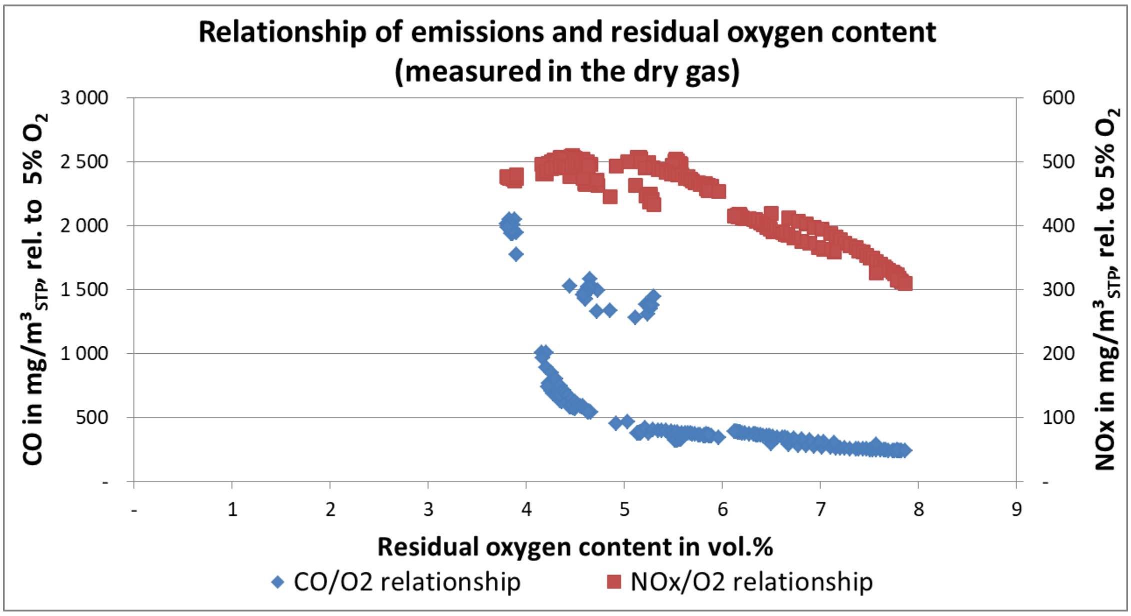

Figure 3: Relationship of emissions and residual oxygen content

In Figure 4 the relationship of temperature of the process gas with the electrical power is shown. It can be seen that at increasing temperature also the electrical power increases. In addition to this characteristic curve two other curves were added in order to illustrate the reason for the change of the temperature of the process gas. At higher residual oxygen content due to the increase of the amount of supply air (apparent by the velocity of the supply air v) the temperature of the process gas decreases.

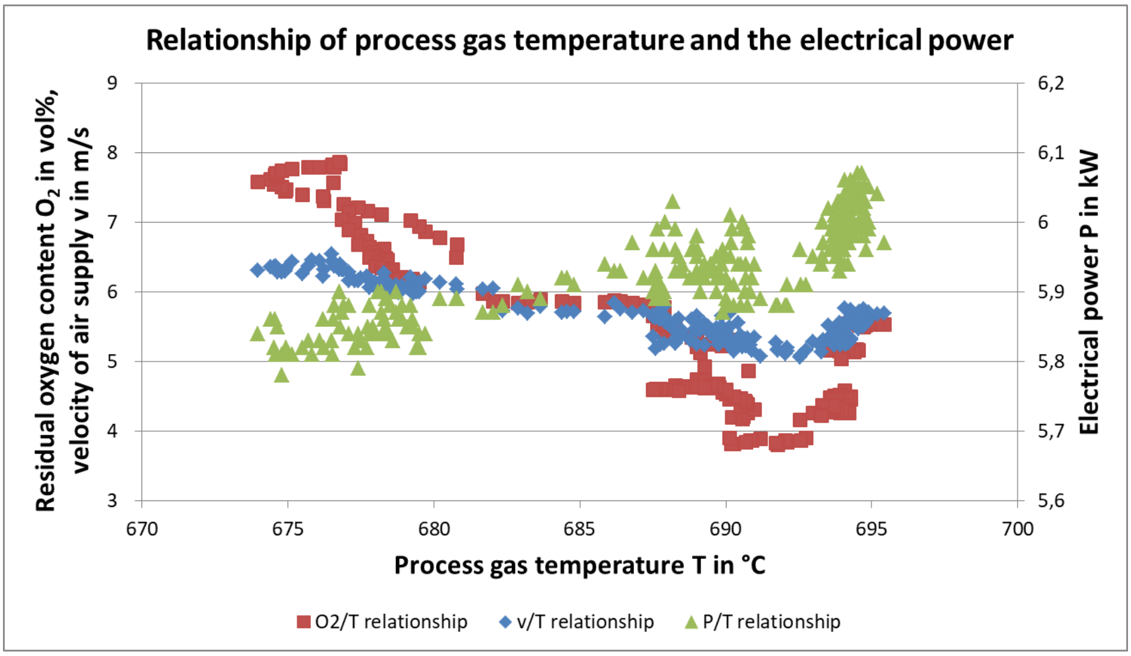

Figure 4: Relationship of the temperature of the process gas and the electrical power

3.5 Conclusion

The tests revealed that the Stirling engine of the type G600i is suitable for lean gas operation with sewage gas. Electrical efficiencies (generator to gross power related to the lower heating value) of above 30% could be achieved. Emission values depend on the combustion conditions (residual oxygen content). At a too low residual oxygen content in the exhaust gas the threshold for nitrogen oxides moves towards the threshold of the “TA Luft” for lean gas engines or rather for four stroke Otto engines (as normal spark ignition engines) at the operation of sewage gas and biogas. At appropriate adjustment the thresholds for cogeneration units in Austria and combustion engines in Germany can be observed.

The electrical power was constantly above 6 kW gross power.