report

bericht

bioenergy2020+

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Test Report - Lean Gas Test

Operation of a Stirling engine with biogas

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Table of Content

1. Introduction

In this report we present the test procedure and the results of a Stirling engine operated with biogas (lean gas) from a biogas plant in Utzenaich[1]. For this test the Stirling cogeneration unit was used for seven weeks from September 4th, 2019 to October 24th, 2019 at the biogas plant in Utzenaich. The Stirling cogeneration unit was installed on a trailer enabling mobile use. The connections with the biogas plant as well as the electrical connections were facilitated by pipes and cables between trailer and biogas plant. For the test operation the heat was given off into the environment by a heat exchanger installed on the trailer. Figure 1 shows the installed trailer in front of the fermenter of the biogas plant.

Figure 1: Trailer from Frauscher Thermal Motors in front of the fermenter of the biogas plant in Utzenaich.

The test presented in this report was conducted on October 2nd, 2019 at the Ökoenergie Utzenaich GmbH in Weilbolden 17, 4972 Utzenaich.

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 biogas. In particular these are the electrical efficiency factor and the emissions in the exhaust gas.

[1] Ökoenergie Utzenaich GmbH; https://www.oekoenergie-gmbh.at/; accessed on 14/10/2019

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*[2] *"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[3] [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 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[4] 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 50 MW	300 (se.i + sp.i)	250 (other four stroke Otto)	60
TA Luft, 2002	biogas, sewage gas	up to 50 MW	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)

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

[3] NMHC = non-methane hydrocarbons

[4] Source: Federal Ministry for the 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.[5]

[5] 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."[6]

The surveyed engine of the type G600i is specified as follows:

- Serial number: 101
- Cubic capacity: 600 ccm
- Integrated generator in the buffer space

The test setup including the Stirling engine, the lean gas burner, the air preheater, the generator, the heat consumption device and the measurement setup was established on a trailer. This trailer is shown in Figure 1. Because the initial pressure of the biogas in the supply line was too low, a side channel compressor had to be mounted in order to increase the pressure of the biogas for the field measurements. The yellow side channel compressor is shown in Figure 2.

[6] 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 biogas as fuel. The aim was to assess the operational reliability and the technical specifications at the so-called “lean gas operation”. The biogas supply was provided from the biogas plant Utzenaich. The composition of the biogas was not adjusted. During the test day several biogas 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.

In addition to the measurements 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. Beside the gaseous emissions carbon monoxide and nitrogen oxide at these field measurements also other exhaust gas compounds were measured by additional measurement equipment and methods.

The following exhaust gas compounds were additionally assessed:

- Organic gaseous compounds (OGC) by a flame ionisation detector
- Methane (CH_4) by gas chromatography
- Formaldehyde (CH_2O) by the acetyl-acetone method
- Ammonia (NH_3) by a photometer

The organic gaseous compounds were determined with a flame ionization detector of the type M&A Thermo FID.

The methane content was determined in the lab of BIOENERGY 2020+ GmbH in Graz from gas samples, which were taken from the exhaust gas during testing. Therefor a gas chromatograph of the type Agilent 490 Micro GC (used column: Molsieve 5A) was used.

The emissions of formaldehyde and ammonia were determined by collection in impingers and consecutive analysis in the lab. For the collection a defined partial stream of the exhaust gas was conveyed through a cooled solution in an impinger. The gaseous compounds were extracted due to absorption from the gas stream. For the determination of the formaldehyde the solution was then analyzed in cuvettes with by the acetyl-acetone method. The used instrument was a spectral photometer DR 5000 from Hach. The determination of ammonia was also determined by the photometer according to DIN 38406 – E5-1.

In order to dissipate the heat of the Stirling engine an air-water heat exchanger, which was installed on the trailer, was used.

During the test day the engine was operated in a way in order to achieve a defined residual oxygen content in the flue gas of 7 and 8% constantly. Two phases with durations of one hour from steady-state operation were evaluated.

2.3 Evaluation method

For the assessment of the different powers and efficiency factors of the Stirling cogeneration unit the determination of the heat value and the fuel value of the biogas is required. The samples for the determination of the main compounds of the biogas were directly taken from the biogas supply line in the trailer. One sample was taken on the day of the installation of the equipment (01/10/2019) and one sample on the test day (02/10/2019). Therefor the gas was lead into gas bags with a filling capacity of 4 liters. 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]	H2 [%]	O2 [%]	N2 [%]	CH4 [%]	CO2 [%]	H2S [%]	Sum [%]
1	01/10/2019	16:30	4	0.0	0.0	0.0	54.7	47.9	0.0	100.9
2	02/10/2019	16:00	4	0.0	0.0	0.0	54.1	47.9	0.0	100.9
Mean value				0.0	0.0	0.0	54.4	47.9	0.0	100.9
Mean value related to 100%				0.0	0.0	0.0	53.9	47.5	0.0	100.0

Table 3: Composition of the biogas samples and calculation of a mean value.

Because the sum of measuring tolerance is slightly above 100%, the mean values were related to 100%.

During the two test days the methane and carbon dioxide concentrations were very similar.

The moisture of the raw gas was determined on site by a moisture sensor (EE31 from E+E Elektronik). The absolute moisture was <15 g/m^3. This is equivalent with around one mass percent of the exhaust gas. Because of the low moisture content the moisture was not respected in the further evaluations. The determination of the upper and lower heating value was conducted with the data from analysis in dry conditions according to Table 3.

The following parameters were determined for two test evaluation phases:

- Gross power
- 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, NO_x, OGC, CH_2O, and NH_3 related to 5% residual oxygen according thresholds
    - CH_4 in vol%

3. Evaluation and Discussion

3.1 Lower and upper heating value

The lower heating value (LHV) and the upper heating value (UHV) of the biogas were determined using the gas composition presented in Table 3. For the calculation the mean values of CH_4, H_2, H_2S, related to 100%, were used resulting in the following fuel specifications:

- LHV: 5,31 kWh/m^3_{STP}
- UHV: 5,89 kWh/m^3_{STP}

3.2 Evaluation phases

The mean values of the test with steady-state conditions on October 2nd, 2019 in phase 1 (10:30 to 11:30) and phase 2 (13.00 to 14:00) are presented in Table 4.

Parameters	Phase 1	Phase 2	Unit
Residual oxygen content	7.7	7.7	vol.%
Gas amount per hour*	4.10	4.07	m^3/h
Power of the gas burner related to the LHV	21.71	21.60	kW
Power of the gas burner related to the UHV	24.09	23.95	kW
Electrical power (generator-gross power)	6.10	6.13	kW
Overall cooling power	10.46	10.42	kW
Electrical efficiency (gross power to LHV)	28.1	28.4	%
Electrical efficiency (gross power to UHV)	25.3	25.6	%
Efficiency of the engine related to LHV	76.3	76.6	%
Efficiency of the engine related to UHV	68.7	69.1	%
CO	132	130	mg/m^3_{STP}, rel. to 5% O_2
NO_x	257	256	mg/m^3_{STP}, rel. to 5% O_2
OGC	~2	~2	mg/m^3_{STP}, rel. to 5% O_2

*****related to standard temperature and pressure

Table 4: Evaluation of the experiment

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

The results indicate that the carbon monoxide emissions were approximately at 130 mg/m^3_{STP} and the nitrogen oxide emissions approximately at 260 mg/m^3_{STP}.

The electrical efficiency was slightly above 28% (gross power to LHV).

3.3 Additional measurements

Because of high efforts and longer preparation time the additional measurements of formaldehyde, ammonia and methane were conducted during the test day but not directly during phase 1 and phase 2. However, because there were always stationary conditions the results could be used for relations with results of phase 1 and phase 2.

Two impinger measurements for formaldehyde and ammonia were conducted respectively.

The mean values of the results are presented in Table 5.

Parameter	Value	Unit
Formaldehyde	<0.5	mg/m³$_{STP}$, rel. to 5% O_2
Ammonia	<1.5	mg/m³$_{STP}$, rel. to 5% O_2
Methane	≤0.003	Vol.%

Table 5: Results of additional measurements

The measurement value for formaldehyde was below detection limit of 0.5 mg/m³$_{STP}$ (rel. to 5% O_2). The ammonia value was below 1.5 mg/m³$_{STP}$ (rel. to 5% O_2). The methane content in the exhaust gas was also below the detection limit of 0.003 vol%.

3.4 Conclusion

The tests revealed that the Stirling engine of the type G600i with the series number 101 is suitable for lean gas operation with biogas. Electrical efficiencies (generator to gross power related to the lower heating value) of above 28% could be achieved. The carbon monoxide emissions of approximately 130 mg/m³$_{STP}$ (rel. to 5% O_2) as well as nitrogen oxide emissions of approximately 260 mg/m³$_{STP}$ (rel. to 5% O_2) at the defined residual oxygen content in the exhaust gas of 7.7% were below the thresholds for cogeneration unit in Austria respectively combustion engines in Germany.

At the additional measurements of gaseous emissions very low emission values were achieved. The organic gaseous compounds were approximately 2 mg/m³$_{STP}$. The methane emissions of ≤0.003 vol% and the formaldehyde emissions of <0.5 mg/m³$_{STP}$ were both below the measurement range. The ammonia emissions of < 1.5 mg/m³$_{STP}$ were also very low. All emission values in mg/m³$_{STP}$ were related to a residual oxygen content of 5%.

The electrical power was constantly above 6 kW gross power.