bericht
report

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Test Report - Lean Gas Test

Operation of a Stirling engine with landfill gas

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1. Introduction

In this report we present the test procedure and the results of a Stirling engine operated with landfill gas (lean gas) at the landfill site in Ort im Innkreis[1] on February 5th, 2020. The whole field measurement with Stirling engines from Frauscher Thermal Motors at the landfill site was conducted during four weeks from January 8th, 2020 to February 5th, 2020. The Stirling cogeneration unit was installed on a trailer enabling mobile use. The landfill gas supply and the electrical connections were facilitated by pipes and cables between trailer and a nearby technique container. In this container a compressor was installed which compresses the gas for the combustion in an internal combustion engine. Though, during the tests with the Stirling cogeneration unit this gas compressor and the internal combustion engine were not used. The landfill gas was directly taken from the gas storage. For the test operation the heat was given off into the surroundings by a heat exchanger which was installed on the trailer. Figure 1 shows the installed trailer in front of the gas tank of the landfill.

Figure 1: Trailer from Frauscher Thermal Motors in front of the landfill gas storage in Ort im Innkreis.

The test presented in this report was conducted on February 5th, 2020 at the Müllverwertungs- und Mülldeponiebetriebs GesmbH in Aichberg 4 in 4974 Ort im Innkreis.

[1] Müllverwertungs- und Mülldeponiebetriebs GesmbH; Aichberg 4; 4974 Ort im Innkreis

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 landfill 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*[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 Austrian thresholds for the operation of cogeneration unit with sewage gas, biogas, wood gas and landfill gas 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.

[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

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)

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, page 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. According to the company Frauscher Thermal Motors 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 engine of the type G600i used on 5 February is specified as follows:

- Serial number: 100
- 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 2. Because the initial pressure of the landfill gas in the supply line was too low, a side channel blower was mounted in order to increase the pressure of the landfill gas. The yellow side channel blower 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 landfill gas as fuel. The aim was to assess the operational reliability and the technical specifications at the so-called “lean gas operation”. The landfill gas supply was provided from the landfill site in Ort im Innkreis. The composition of the landfill gas was not adjusted. During the test day several landfill gas samples were taken for the analysis in the lab of BEST GmbH. A gas chromatograph of the type Agilent 490 Micro GC (used column: Molsieve 5A) was used.

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) and dries it 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 organic gaseous compounds were measured with a flame ionization detector of the type M&A Thermo FID. The determination of the methane content was accomplished by gas samples which were extracted from the exhaust gas and determined in the lab in Graz of BEST GmbH. Therefor a gas chromatograph of the type Agilent 490 Micro GC (used column: Molsieve 5A) was used.

The additional measurements of formaldehyde and ammonia which was conducted at the biogas plant[7] in Utzenaich were omitted. Because the combustion conditions of the Stirling cogeneration unit, regardless of the used lean gas type, were constant it can be assumed that the landfill gas has similarly low values as the used biogas. The determined values from the biogas plant were for formaldehyde below the detection limit of 0.5 $mg/m^3{}_{STP}$ (rel. to 5% O_2) and for ammonia below 1.5 $mg/m^3{}_{STP}$ (rel. to 5% O_2). Lowest formaldehyde values in the exhaust gas because of steady operation of Stirling cogeneration-units is also confirmed in the scientific report of FZKA-BWPLUS on page 164 of Reutlingen University by a measurement of the LUBW (State Office for the Environment, Measurements and Nature Conservation of the Federal State of Baden-Württemberg). There it is stated that the constant flame in Stirling engines which burns lean gas continuously can be the explanation that no problems due to high concentrations of formaldehyde and other aldehydes occur because these compounds are intermediate products during combustion (FZKA-BWPLUS[8] on page 98).

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 exhaust gas of 6 and 8%. After the second operation phase a particle measurement for 15 minutes was conducted with a Wöhler SM500.

2.3 Evaluation method

For the determination of the different powers and efficiencies of the Stirling cogeneration unit the determination of the lower and upper heating values (LHV, UHV) of the landfill gas is required. The samples for the determination of the main components of the landfill gas were directly taken from the supply pipe in the trailer. Two samples were taken on the test day (February 5th, 2020). Therefor the gas was lead into gas bags with a filling capacity of 3 liters. The samples were analyzed in the lab of BEST 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 [%]	Sum [%]
1	05.02.2020	12:25	3	0.5	23.4	55.1	20.9	100.0
2	05.02.2020	14:10	3	0.8	23.7	55.4	20.1	100.0
Mean value				0.7	23.6	55.3	20.5	100.0

Table 3: Dry gas composition of the landfill gas samples as well calculation of the mean values (results of the analysis are related to a sum of 100%)

[7] Messbericht Schwachgasversuch, Betrieb eines Stirlingmotors mit Biogas vom 14.10.2019: https://www.frauscher-motors.com/wp-content/uploads/2019/10/N101340_Biogasversuche_20191002.pdf

[8] Bernd T., etal; Forschungsbericht FZKA-BWPLUS: Gekoppelte Produktion von Kraft und Wärme aus Bio-, Klär- und Deponiegas in kleinen, dezentralen Stirling-Motor Blockheizkraftwerken; Förderkennzeichen: BWK 25008 – 25010; Hochschule Reutlingen; März 2009

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 the two test phases:

- Gross power of the generator
- Lower heating value of the fuel per m^3
- Upper heating value of the fuel per m^3
- Efficiencies (gross power and overall power related to the lower and the upper heating value)
- Gas amount and gas power
- Emissions
  - CO, NO_x, OGC, rel. to 5% residual oxygen content acc. to threshold
  - CH_4 in vol%

3. Evaluation and Discussion

3.1 Lower and upper heating value

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

- LHV: 5,52 kWh/m^3_{STP}
- UHV: 6,12 kWh/m^3_{STP}

3.2 Evaluation phases

The mean values of the test with steady-state conditions on February 5th, 2020 in phase 1 (11:55 to 12:25) and phase 2 (13.40 to 14:10) are presented in Table 4.

Parameters	**Phase 1**	**Phase 2**	**Unit**
Residual oxygen content	6.7	7.3	vol.%
Gas amount per hour*	3.82	3.99	m^3/h
Power of the gas burner related to the LHV	21.09	22.01	kW
Power of the gas burner related to the UHV	23.38	24.40	kW
Electrical power (gross power)	6.32	6.60	kW
Overall cooling power	8.82	8.89	kW
Electrical efficiency (gross power to LHV)	30.0	29.9	%
Electrical efficiency (gross power to UHV)	27.0	27.0	%
Overall efficiency of the engine related to LHV	71.8	70.3	%
Overall efficiency of the engine related to UHV	64.8	63.4	%
CO	310	224	mg/m^3_{STP}, rel. to 5% O2
NO_x	270	287	mg/m^3_{STP}, rel. to 5% O2
OGC	~2	~4	mg/m^3_{STP}, rel. to 5% O2

***related to standard temperature and pressure**

Table 4: Evaluation of the experiment

The particle measurement of 15 minutes during operation phase 1 with a Wöhler SM500 revealed a total particle concentration of 9 mg/m^3_{STP}, related to 5% O_2.

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 for phase 1 the carbon monoxide emissions were at 310 mg/m³$_{STP}$ and the nitrogen oxide emissions at 270 mg/m³$_{STP}$. The organic gaseous compounds of 2 mg/m³$_{STP}$ were very low

In phase 2 the carbon monoxide emissions were at 224 mg/m³$_{STP}$ and the nitrogen oxide emissions at 287 mg/m³$_{STP}$. The organic gaseous compounds of 4 mg/m³$_{STP}$ were also very low.

The methane content in the exhaust gas was for both, phase 1 and phase 2, below the detection limit of the gas chromatograph and could not be determined.

The electrical efficiency was at 30% (gross power to LHV).

3.3 Conclusion

The tests revealed that the Stirling engine G600i with the serial number 100 is suitable for lean gas operation with landfill gas. An electrical efficiency (gross-power to lower heating value) of 30% was achieved. The carbon monoxide emissions were at 310 mg/m³$_{STP}$ in phase 1 and at 224 mg/m³$_{STP}$ in phase 2 (rel. to 5% O_2). The nitrogen oxide emissions were at 270 and 287 mg/m³$_{STP}$ (rel. to 5% O_2) respectively. Consequently the emissions are below the current thresholds for cogeneration units in Austria or for combustion engines in Germany.

The particle emissions in phase 2 were slightly below 9 mg/m³$_{STP}$ (rel. to 5% O_2).

At the additional measurements very low values of gaseous emissions could be achieved. The organic gaseous compounds were below 5 mg/m³$_{STP}$. The methane content in the exhaust gas was in both, phase 1 and phase 2, below the detection limit of the gas chromatograph and could not be determined because of the low concentrations.

The electrical power was constantly above 6.3 kW for phase 1 and 6.6 kW for phase 2 respectively.