report

bericht

Harald Stressler

Stefan Aigenbauer

Test Report - Lean Gas Test

Simulated lean gas in the laboratory

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Project manager Stefan Aigenbauer
stefan.aigenbauer@bioenergy2020.eu

Employees Harald Stressler
harald.stressler@bioenergy2020.eu

Scientific partner Frauscher Thermal Motors GmbH

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BIOENERGY 2020+ GmbH

Location Wieselburg
Gewerbepark Haag 3
A 3250 Wieselburg-Lan
T +43 (0) 7416 52238-10
F +43 (0) 7416 52238-99
office@bioenergy2020.eu
www.bioenergy2020.eu

Head Office Graz
Inffeldgasse 21b, A 8010 Graz
FN 232244k
District Court Graz
VAT-No. ATU 56877044

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Report

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1. Introduction

In this report we present the test procedure and the results of a Stirling engine operated with simulated lean gas.

This test was conducted with a Stirling cogeneration unit of the series alphagamma® G600i in the laboratory of Frauscher Thermal Motors GmbH on August 8th, 2019. The Stirling engine was operated with synthetic lean gas (with nitrogen and diluted natural gas). The content of natural gas was gradually decreased in order to be able to evaluate the technical specifications of the cogeneration unit at very low methane content.

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.

[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 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.[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. 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."[5]

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

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

2.2 Experimental procedure

The Frauscher alphagamma® Stirling G600i was operated with diluted natural gas as fuel. For the assessment of the operational reliability and the technical specifications at the so-called "lean gas operation", nitrogen was gradually added in order to decrease the natural gas content successively.

Different lean gas quantities were simulated. Prior to the test the engine was operated overnight with pure natural gas under steady-state conditions, enabling to start the lean gas tests at operating temperature. On the next morning data from operation with pure natural gas were logged in a ten minute interval. This data provide reference values for the subsequent lean gas tests.

Thereafter the engine was operated with two different lean gas blends (21.4% and 17.4% natural gas) with a measurement interval of 30 minutes in each case. Prior to the respective

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

measurement interval the engine was brought to constant operation conditions. It took about half an hour from the adjustment of the lean gas composition until the stationary operation (constant temperatures of the engine) were achieved.

After measuring the two lean gas operation points the natural gas content was decreased. The aim was to evaluate the minimum value for which the burner of the engine still works. After the two steady-state phases three further phases with duration of 10 minutes respectively were measured and evaluated.

The measurement of further operation points was conducted without adjusting steady-state operation phases. Though, the operation points did not reveal high fluctuations of temperature and pressure.

The engine control was adjusted according the set point of the process gas temperature on the hot side of 700 °C. At this operation point the electrical gross power remains very constant. With the reduction of the natural gas content the volume flow clearly increased due to addition of more and more nitrogen leading to a higher gas volume flow and consequently to a higher pressure drop in the burner as well as in the gas control system.

2.3 Evaluation method

The following parameters were determined for the respective measurement intervals:

- Gross power of the generator
- Feed-in power of the whole machine
- Upper heating value of the fuel
- Lower heating value of the fuel
- Efficiency (gross power and overall power related to the lower and the upper heating value respectively)
- Gas amount
- Emissions

Natural gas from the gas grid in Upper Austria was used as fuel. For the calculations the mean value of the lower heating value and the upper heating values of the last six natural gas analysis were used. The analysis of natural gas is conducted semi-annually and provided by Netz Oberösterreich GmbH. The mean values from the analysis are presented in Table 3. They are calculated from the analysis from January 11th, 2017 to July 2nd, 2019.

Parameter	Unit	Mean values
CO_2	mol%	0.47
N_2	mol%	0.53
CH_4	mol%	95.72
C_2H_6	mol%	2.79
C_3H_8	mol%	0.34
i-C_4H_{10}	mol%	0.06
n-C_4H_{10}	mol%	0.05
i-C_5H_{12}	mol%	0.02
n-C_5H_{12}	mol%	0.01
C_6+	mol%	0.03
rel. density		0.58
Wo	kWh/m^3_{STP}	14.81
UHV	kWh/m^3_{STP}	11.29
LHV	kWh/m^3_{STP}	10.19

Table 3: Mean values of the fuel composition according to Netz Oberösterreich GmbH

3. Evaluation and Discussion

3.1 Overall results

The results of the single test intervals are presented in Table 4:

Test number	-	Reference	1	2	3	4	5
Machine	-		G600i	G600i	G600i	G600i	G600i
Nitrogen amount	m^3_{STP}/h	0	8.15	10.95	12.7	13.5	14.5
Natural gas content	vol%	100.0%	21.4%	17.4%	15.5%	15.1%	14.1%
Date	dd.mm.yyyy	08/08/2019	08/08/2019	08/08/2019	08/08/2019	08/08/2019	08/08/2019
Time start	hh:mm:ss	09:05:00	12:16:00	13:43:00	14:37:00	14:55:00	15:20:00
Time stop	hh:mm:ss	09:19:00	12:46:00	14:13:00	14:47:00	15:05:00	15:30:00
Gas amount	m^3_{STP}/h	2.001	2.218	2.314	2.338	2.395	2.388
Power of gas burner related to UHV	kW	22.60	25.05	26.13	26.41	27.05	26.97
Power of gas burner related to LHV	kW	20.39	22.60	23.58	23.83	24.41	24.33
Electrical gross power	kW	6.215	6.238	6.248	6.215	6.330	6.248
Feed-in power	kW	5.832	5.772	5.776	5.727	5.819	5.743
Overall cooling power	kW	10.67	10.68	10.70	10.68	10.69	10.68
Pressure in burner	Pa	576	1809	2570	3113	3388	3613
Exhaust gas temperature	°C	153	226	246	257	263	268
Electrical efficiency (gross power to UHV)	%	27.5%	24.9%	23.9%	23.5%	23.4%	23.2%
electrical efficiency (gross power to LHV)	%	30.5%	27.6%	26.5%	26.1%	25.9%	25.7%
Electrical efficiency (feed-in power to UHV)	%	25.8%	23.0%	22.1%	21.7%	21.5%	21.3%
Electrical efficiency (feed-in power to LHV)	%	28.6%	25.5%	24.5%	24.0%	23.8%	23.6%
Overall efficiency (cooling power + gross power) rel. to UHV	%	74.7%	67.5%	64.8%	64.0%	62.9%	62.8%
Overall efficiency (cooling power + gross power) rel. to LHV	%	82.8%	74.9%	71.9%	70.9%	69.7%	69.6%
Overall efficiency (cooling power + feed-in power) rel. to UHV	%	73.0%	65.7%	63.0%	62.1%	61.0%	60.9%
Overall efficiency (cooling power + feed-in power) rel. to LHV	%	81.0%	72.8%	69.9%	68.9%	67.6%	67.5%
CO	ppm	571	149	123	119	108	113
NOx	ppm	757	45	26	18	18	14
O_2	vol%	6.0	5.8	5.7	5.7	5.7	5.8
CO rel. to 5% O_2	mg/m^3_{STP}	762	196	161	156	142	148
NOx tel. to 5% O_2	mg/m^3_{STP}	1662	97	57	39	38	30

Table 4: Results of the test intervals

The electrical gross power was constant in each test interval. The electrical efficiency achieved 30% in the reference operation with natural gas (gross power to LHV). At lean gas operation the efficiency decreased by approximately 3 to 5 percentage points.

Due to the higher volume flow at the additions of nitrogen the pressure drop in the system clearly increased. In order to compensate this pressure drop the pressure in the natural gas line had to be increased. At a constantly controlled temperature of the process gas of 700 °C this lead to a higher burner power at lean gas operation. At constant electrical gross power a lower electrical efficiency at lean gas operation could be calculated.

Characteristic curves:

The engine was always operated at the same operation point regarding process temperature (set point= 700 °C). The gross power of the different intervals is presented in Figure 1.

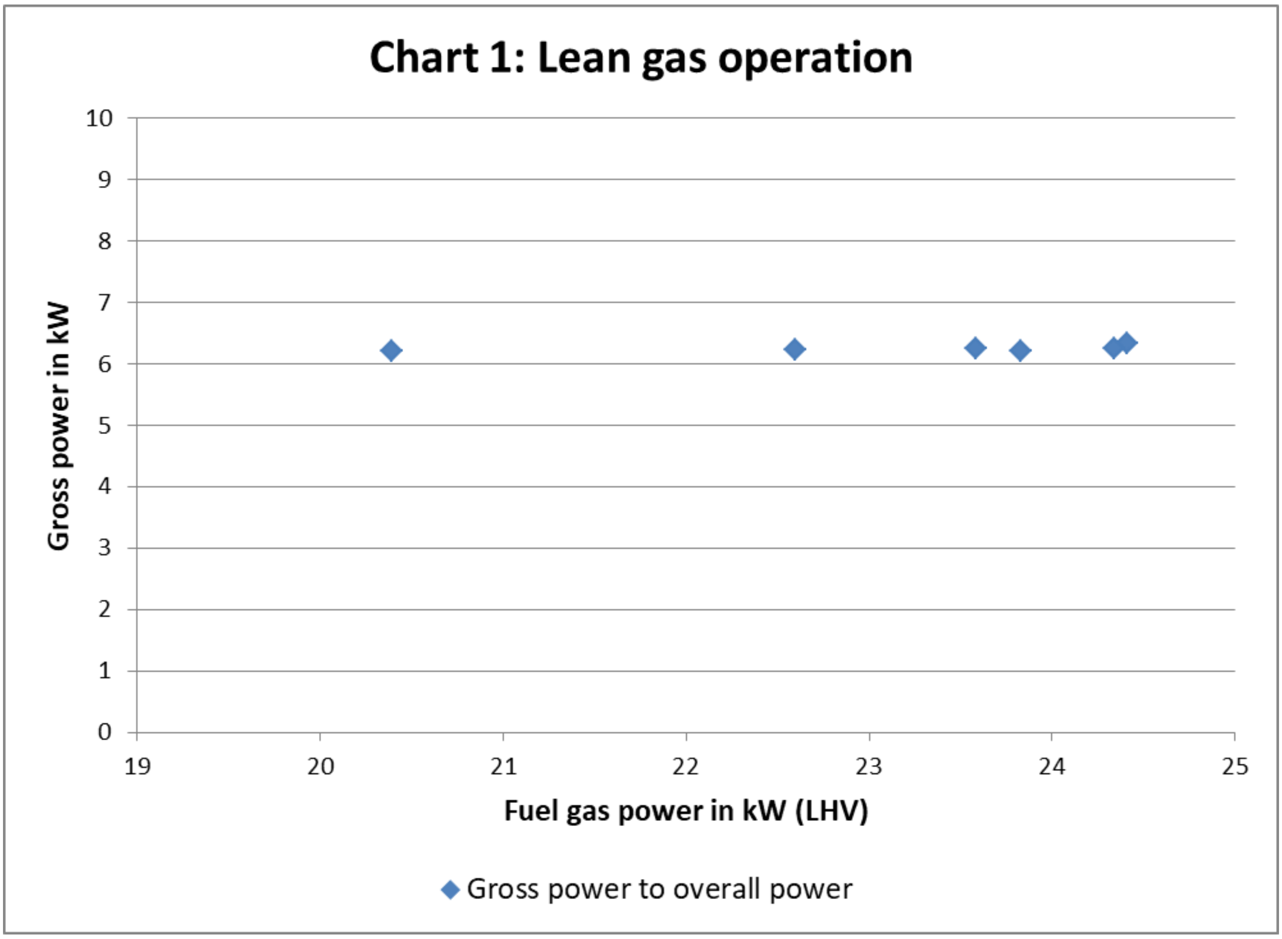

Figure 1: Relationship of gross power and overall power

The increasing fuel power at lean gas operation due to change of the pressure conditions (as described above) at constant temperature of the process gas lead to a decreasing electrical efficiency. This relationship is presented in Figure 2.

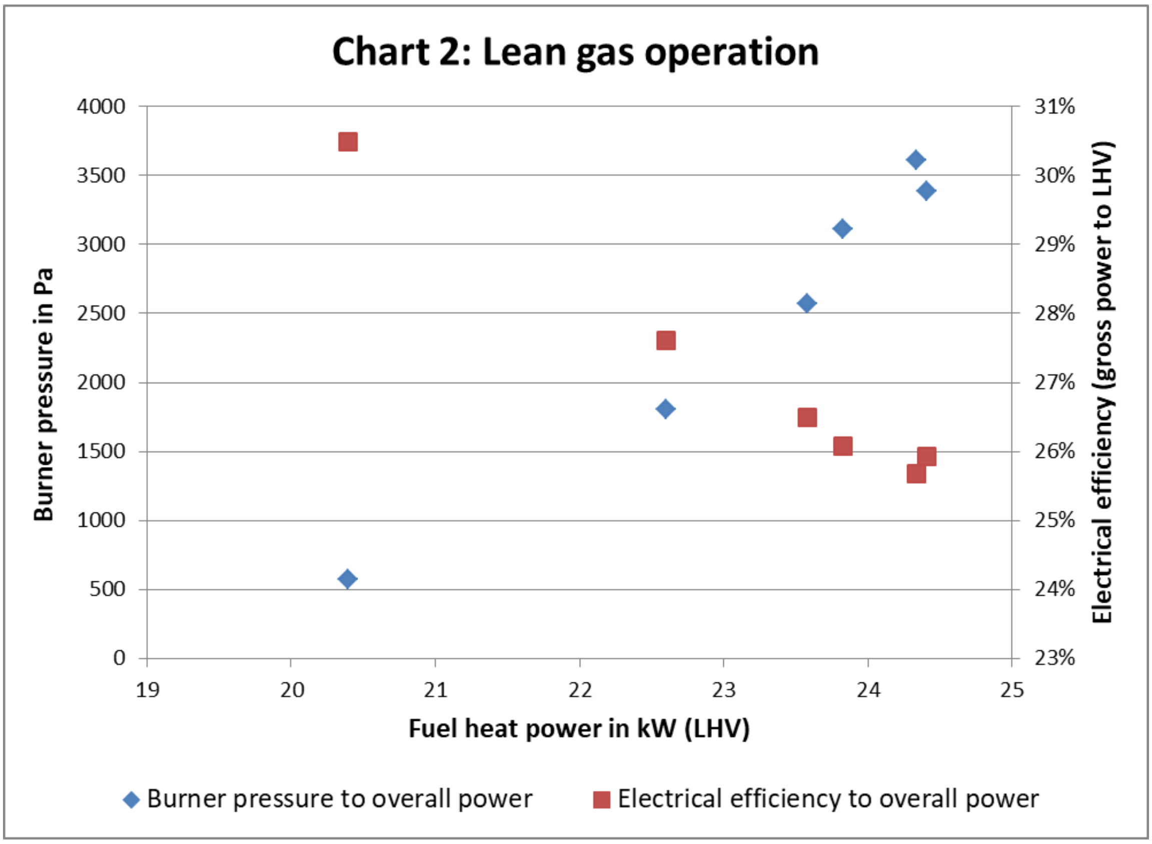

Figure 2: Relationship of pressure in the burner and electrical efficiency with the overall power.

The lean gas operation could be realized until to a natural gas content of 14.1% in the combustion gas.

The electrical efficiency related to the natural gas content in the combustion gas is presented in Figure 3. In this figure is can be seen that the electrical efficiency (gross efficiency) decreases with declining natural gas content. At lean gas operation more natural gas or rather a higher fuel heat capacity is required in order to achieve the set point temperature of 700 °C for the process gas on the hot side. Due to the higher exhaust gas mass flow and the higher exhaust gas temperatures the losses increase resulting in a decrease of the overall efficiency.

In Table 5 the power ratings as well as the different losses of the single tests are presented. It can be clearly seen that exhaust gas losses because of higher exhaust gas mass flow and higher exhaust gas temperatures increase. The exhaust gas power increased at natural gas operation with 1.27 kW to 4.57 kW at the last lean gas operation (natural gas content: 14.1%).

The miscellaneous losses which summarizes radiation, heat conduction and convection was rather constant in the lean gas tests. The miscellaneous loss accounted for 2.23 kW to 3.03 kW.

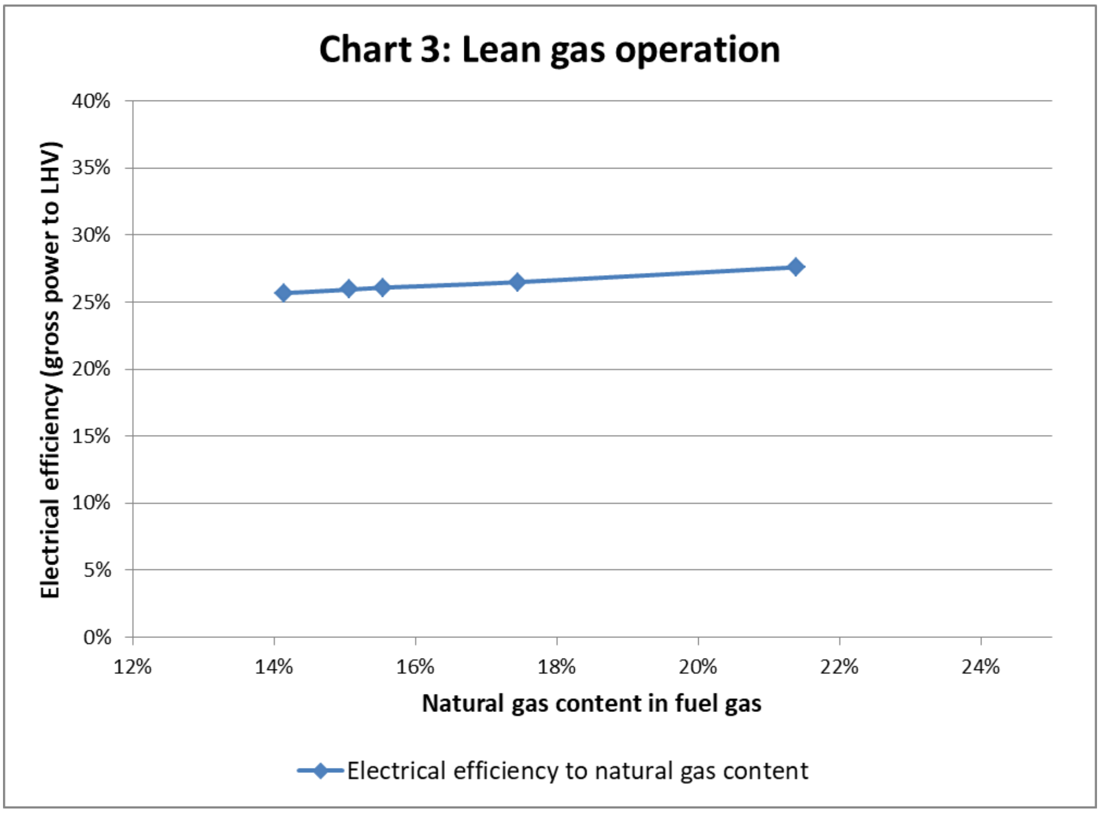

Figure 3: Relationship of electrical efficiency and natural gas content

Test number	-	Reference	1	2	3	4	5
Machine	-	G600i	G600i	G600i	G600i	G600i	G600i
Nitrogen amount	mn³/h	0	8.15	10.95	12.7	13.5	14.5
Natural gas content	vol%	100.0%	21.4%	17.4%	15.5%	15.1%	14.1%
Date	dd/mm/yyyy	08/08/2019	08/08/2019	08/08/2019	08/08/2019	08/08/2019	08/08/2019
Time start	hh:mm:ss	09:05:00	12:16:00	13:43:00	14:37:00	14:55:00	15:20:00
Time stop	hh:mm:ss	09:19:00	12:46:00	14:13:00	14:47:00	15:05:00	15:30:00
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Electrical gross power	kW	6.215	6.238	6.248	6.215	6.330	6.248
Feed-in power	kW	5.832	5.772	5.776	5.727	5.819	5.743
Overall cooling power	kW	10.67	10.68	10.70	10.68	10.69	10.68
Overall power	kW	16.89	16.92	16.95	16.90	17.02	16.93
Overall efficiency	%	82.84	74.87	71.87	70.92	69.73	69.57
Losses	kW	3.50	5.68	6.63	6.93	7.39	7.41
Exhaust gas losses	kW	1.27	2.95	3.68	4.10	4.36	4.57
Radiation losses	kW	2.23	2.73	2.95	2.83	3.03	2.84

Table 5: Distribution of the losses of the different tests

3.2 Emissions

The carbon monoxide as well as the nitrogen oxide emissions at lean gas operation were clearly below the thresholds of the “TA Luft” for combustion engines which are operated with sewage gas or biogas. The emissions are presented in Figure 4. The thresholds for carbon monoxide are 1000 mg/m^3_{STP} and for nitrogen oxides 500 mg/m^3_{STP}, both related to 5% residual oxygen content.

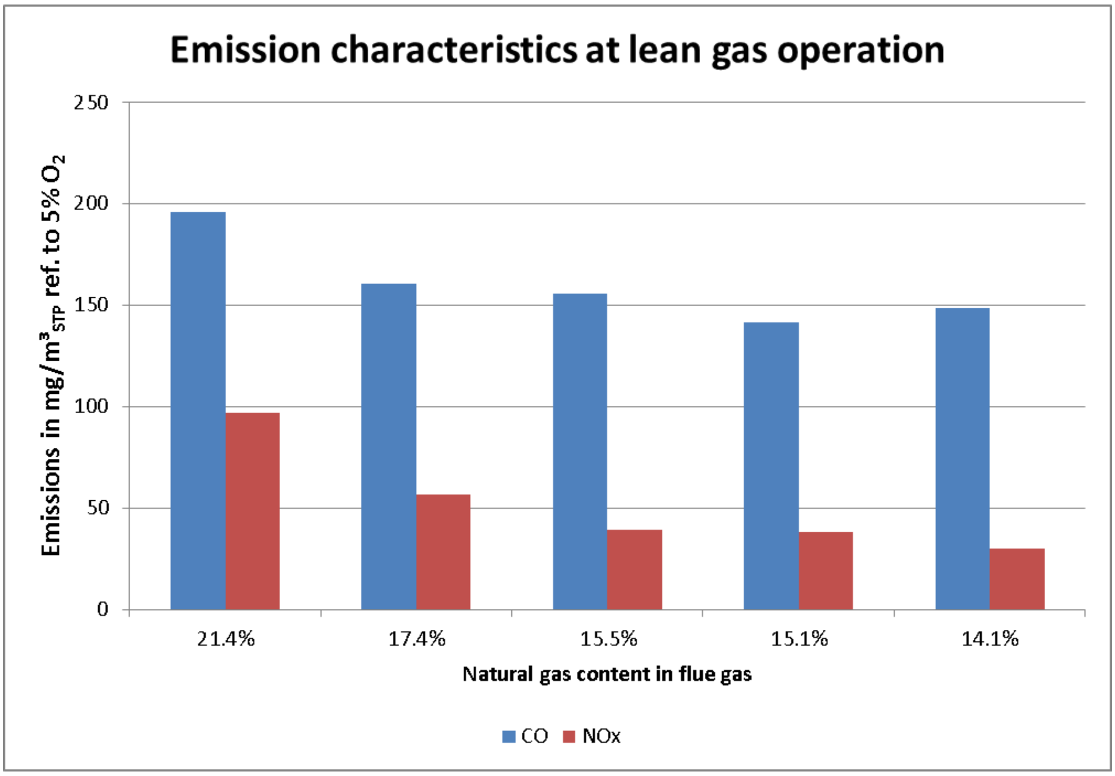

Figure 4: Emission characteristics at lean gas operation

3.3 Conclusion

The tests revealed that the Stirling engine G600i from Frauscher Thermal Motors GmbH is suitable for lean gas operation at lowest natural gas content at operating conditions. In further tests a cold start with lean gas will be investigated.

The natural gas content in the fuel gas could be decreased to 14.1%. A further reduction of the natural gas content in the fuel gas could be realized when the pressure drop would be reduced or rather the fuel gas would be compressed (side channel compressor in the fuel gas line). In order to operate the engine at further lean gas applications at the optimum operation point, a preparation of the lean gas regarding the needed line pressure is required.

At the operation with pure natural gas the engine achieved an electrical efficiency of above 30% (gross power to LHV). At a natural gas content of 14.1% the efficiency decreased to slightly below 26%.

The emissions comply with the thresholds in §15a Verordnung in Austria and the "TA Luft" in Germany for cogeneration units respectively for combustion engines. The emission values for lean gas operation were between 150 and 200 mg/m^3_{STP} for carbon monoxide and 30 and 100 mg/m^3_{STP} for nitrogen oxides.