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DEVELOPING A BURNER SYSTEM FOR LOW CALORIFIC GASES IN MICRO GAS TURBINES: AN APPLICATION FOR SMALL SCALE DECENTRALIZED HEAT AND POWER GENERATION

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1. ABSTRACT

Gases with a low calorific value (LCV) are produced by many different processes, both natural and industrial. They are released from landfill sites, coal mines or sewage treatment plants, or they may be by-products of industrial processes, for example in the steel or chemical industry. In recent years, these fuel gases have received increasing interest as alternative fuel sources. They are especially suited to small-scale decentralized heat and power generation. The lower calorific values of these gases range from 1 to 3 kWh/m3 (natural gas, for comparison's sake has about 10-12 kWh/m3). This is due to the large amounts of inert components such as nitrogen or carbon dioxide which can be found in these gases, the combustible species usually being methane, hydrogen and carbon monoxide.

While the use of these gases is desirable from both economic and ecological points of view, the utilization of such fuels in technical systems poses some challenges. The composition and hence heating values of these gases may change quite drastically over time; also they may contain hazardous substances such as siloxanes or H_2S, raising corrosion issues. These issues have to be taken into account when designing a burner system for such fuels. Today, low calorific gases are often utilized in combined heat and power gas engines. However, these engines are restricted to fuel gases with a minimum CH_4 content of 38 vol-% for economic reasons. Micro gas turbines (MGT), however, present an interesting alternative to utilize these gases for decentralized heat and power generation since they can handle gases with much lower CH_4 contents and varying compositions, an important consideration with low quality fuels. Also, MGTs are efficient at partial loads and can maintain low CO and NO_X emissions, making them an interesting option for the utilization of low calorific fuel gases.

In the course of a German research project, Gaswärme-Institut e. V. (GWI), in cooperation with the Ruhr-University Bochum and Fraunhofer Institute UMSICHT, developed and implemented a flexible combustion system for micro gas turbines in order to utilize gases with a low calorific value as fuel, an application which is especially suited for the small scale decentralized heat and power generation with locally available fuel gases. A burner based on the principle of continuously staged air with internal recirculation (COSTAIR) was designed, optimized and finally put to the test under realistic operating conditions in an off-the-shelf micro gas turbine.

In a first step, the COSTAIR burner was investigated both numerically and experimentally in the original combustion chamber of a micro gas turbine under atmospheric conditions, burning different fuel gases with low calorific values. The results were used to develop an optimized burner design which achieves a safe and stable operation with total air ratios up to 8.5. The CO and NO_X emissions remain low over the entire operational range.
In a second step, this burner was tested on a landfill site in continuous operation, burning a locally available landfill gas with CH_4 contents ranging from 16 vol-% to 30 vol-%. Both safe operation and low pollutant emissions were observed, no material fatigue was detected.

In the final phase, the combustion system was adapted to an existing micro gas turbine. As the micro gas turbine was originally designed to be used with natural gas, modifications had to be made for low calorific gases. In order to obtain conclusive information on the combustion behaviour and pollutant emission of the turbine, the validation tests were performed for various methane concentrations in a CH4/N2-mixture which served as a fuel gas of low calorific value. Also, the impact of a pilot burner was investigated.

The measurements show that the combustion system designed in this project allows a stable and clean combustion of gases with a low calorific value down to 1.2 kWh/Nm^3 (corresponding to a CH_4 concentration of about 14 vol -%). In general, it could be shown that the combination of a COSTAIR burner system optimized for low calorific gases and a micro gas turbine provides for an efficient and environmentally friendly means to utilize low quality fuel gases.

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2. INTRODUCTION

Many processes, both natural and industrial, produce gases with a low calorific value (LCV). Such gases are released in landfill sites, coal mines or at sewage treatment plants, or may be by-products of industrial processes, for example in the chemical or steel industry.

Also, naturally occurring low calorific fuel can be found in numerous locations in Central and Eastern Europe. In Poland, for example, such gases have played an important role in the energy supply of the country for the last twenty years, with an annual consumption of 3.5 billions m^3[1].

In recent years, these low calorific gases have garnered increasing interest world wide as alternative fuels, especially for small scale decentralized heat and power generation applications. The low calorific values of these gases are due to the large amounts of inert species (usually N_2 and/or CO_2), resulting in LCV of less than 3 kWh/m^3. This is about a quarter of the LCV of natural gas, which ranges from 10-12 kWh/m^3. The combustible components generally include methane (CH_4), carbon monoxide (CO) and hydrogen (H_2).

Table 1 shows lower the chemical compositions and calorific values of some typical lower calorific gases which were used in the course of this project, along with natural gas to provide a comparison.

Unfortunately, there are also some challenges which come with the use of low calorific gases as fuel. First of all, composition and hence LCVs and combustion behaviour of low calorific gases often change quite drastically over time. Also, these gases are often contaminated with traces of hazardous substances such as siloxanes or H_2S which can cause corrosion.

At present, low calorific gases are most often used to fuel gas-powered combined heat and power (CHP) engines. These engines, however, are limited to fuel gases with CH_4 concentrations of more than 38 vol-%. The utilization of fuel gases containing lesser amounts of CH_4 with their accordingly lower LCVs is economically unfeasible in gas-powered engines with current combustion technology.

Another disadvantage of gas engines in this context is that the exhaust gases need to be treated in order to comply with emission laws.

Table 1. Low Calorific Gas Compositions and Properties

No.	Reference	Composition [Vol. - %]						LCV H_i [kWh/m^3]
		CH_4	CO	H_2	CO_2	N_2	NH_3	
1	Landfill Gas	10 –30	0	0	0	70 - 90		1 - 3
2	Bio Gas	5	20	15	10	50	<0.1	ca. 1.5
3	Mine Gas	25	0	0	10	65		ca. 2.5
4	Wood Gas	5	15	15	15	50		ca. 1
5	Sewage Gas	35	0	0	55	10		ca. 3.5

H_i (Natural Gas)= 10-12 kWh/m^3

Micro gas turbines (MGT), however, present an interesting and profitable alternative to utilize low calorific gases in CHP processes. Small electrical power outputs (P_{el}< 250kW), and high efficiencies at partial loads as well as low CO and NO_x-emissions make them appear especially suited for de-centralized use of locally available low calorific gases. They can utilize of fuel gases with methane contents of less than 38 vol-%, which would otherwise have to be torched due to environmental concerns. Also, MGT are quite resilient to changes in fuel gas compositions, an important consideration with these low quality fuels. [2,3]

Their simple design, lower costs of investment, operation and maintenance as well as lower noise emissions when compared to gas powered engines also make MGT an interesting option for utilizing locally occurring low calorific fuel gases.

Within the scope of an AiF sponsored research project, GWI in collaboration with several research and industrial partners investigated and optimized the burner concept of continuously staged air with internal recirculation (COSTAIR) for such gases in a micro gas turbine environment. The aim was to replace the burner system in a commercially available MGT with a burner system optimized for the use of low calorific gases.

Atmospheric experiments as well as numerical simulations were carried for a variety of different fuel gases (cf. Table 1) in order to optimize the burner design for this application. A number of different fuel gases were synthesized using a gas mixing facility at GWI.

In a second step, the atmospheric test rig was transported to a landfill site in order to investigate the burner behaviour with an untreated, locally occurring landfill gas over a longer period of time.

Finally, the burner was mounted into an MGT installed at Fraunhofer UMSICHT and tested extensively under real operating conditions.

3. THE COSTAIR-BURNER AND ATMOSPHERIC TESTS

As the acronym COSTAIR implies, this burner uses continuously staged air and internal recirculation within the combustion chamber to obtain a stable combustion with low NOX and CO emissions. This is achieved by means of a centrally mounted air distributor through which air is injected into the combustion space. This distributor also serves to create a recirculation zone which stabilises the flame. Fuel gas nozzles are distributed around the central air distributor. The secondary air inlets are necessary because in contrast to larger gas turbines, there are hardly any vane and blade cooling techniques used in MGT, thus limiting the turbine inlet temperatures to less than 950°C. CFD calculations of the velocity and temperature distributions in such a burner can be seen in Figures 1 and 2.

Prior to the atmospheric experiments performed at GWI's facilities, extensive CFD studies were carried out in order to optimize the burner design, especially with regards to the shape of the air distributor.

The atmospheric test rig used in this project consisted of the combustion chamber of a turbec MGT T100 gas turbine into which the optimized COSTAIR burner was mounted. A mixing facility provided a variety of synthetically produced low calorific fuel gases found in Table 1, while an air pre-heater supplies combustion air with a temperature of 550°C, a typical value for a micro gas turbine. One of the fuel gases was seeded with small amounts of NH_3 in order to investigate the effect of fuel bound nitrogen on the overall NO_X emissions. A suction probe was used to determine CO, CO_2, O_2, NO and NO_2 concentrations in the flue gas.

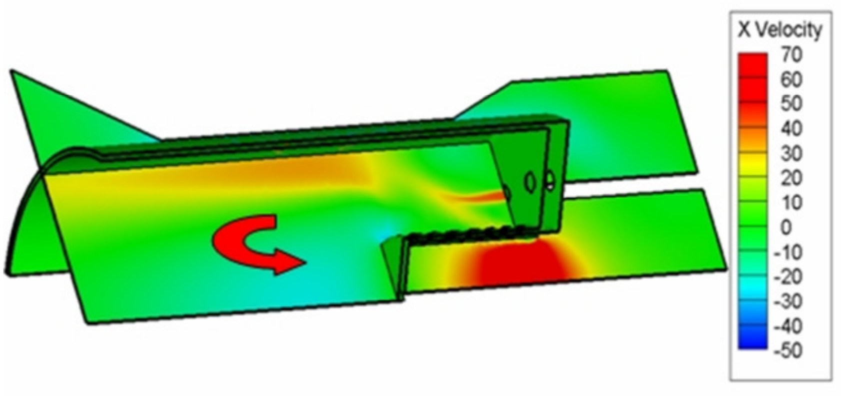

Figure 1: Simulated Velocity Distribution [m/s]

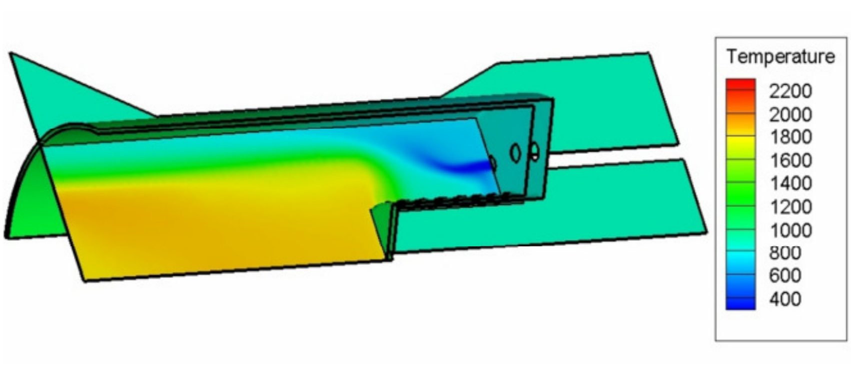

Figure 2: Simulated Temperature Distribution [K]

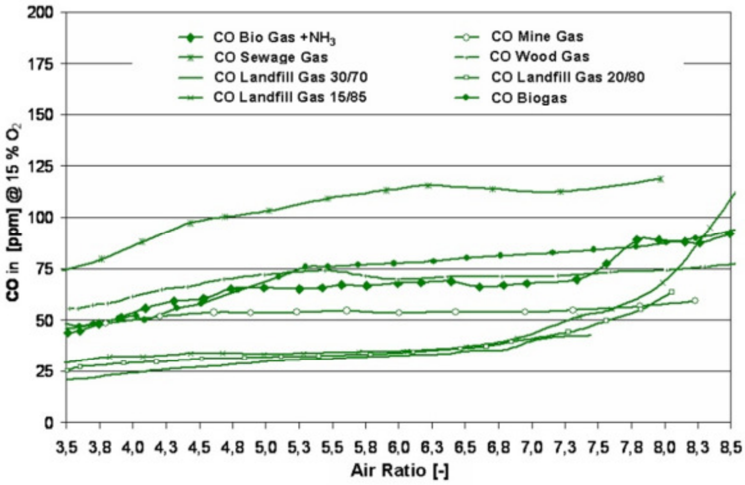

Figure 3: Measured CO Emissions over the Air Ratio

Figures 3 and 4 show the CO and NO_X emissions over the air ratio.

While the CO emissions increase slightly with higher air ratios, indicating the onset of combustion instabilities, the NO_X emissions remain at a low level over the entire range of air ratios. This behaviour is the same for all the fuel gases which were investigated. It can also be seen that if fuel-bound nitrogen is present in the fuel gas, this will have a major impact on the NO_X production of the burner when compared to the thermal NO_X formed via the Zeldovich mechanism.

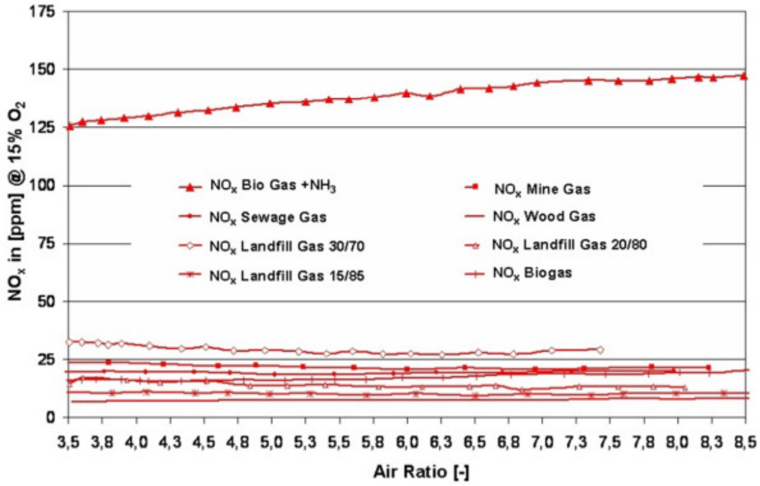

Figure 4: Measured NO_X Emissions over the Air Ratio

4. ON-SITE TESTS AT A LANDFILL SITE

While a variety of low calorific fuel gases was artificially generated at GWI's mixing facility in the first phase, the second phase of this research project investigated the impact of real, non-treated low calorific fuel gas on the behaviour of the burner system. For this purpose, the atmospheric test rig was transported to a landfill site near Frankfurt, Germany. There, the burner was operated continuously for three weeks, using the locally available landfill gas as fuel.

One problem that often occurs with low calorific gases is that their properties and composition can change quite drastically over time. During the three weeks of testing, the methane content of the landfill gas varied between 16 and more than 30 volume percent. Figure 5 shows the time variation curves of several important parameters such as flue gas temperature and CH_4 content in a twelve hour interval.

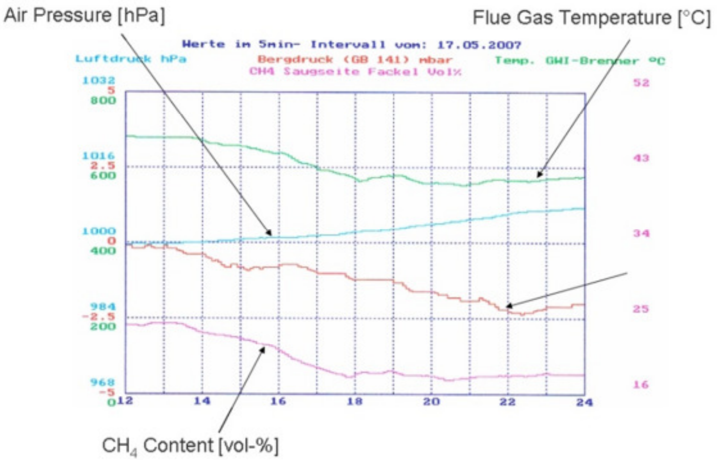

Figure 5: Time Variation Curves (excerpt) from the Experiments at the Landfill Site

Nevertheless, it was found that the COSTAIR burner system could be operated in a safe and stable manner over the entire time. The changes in fuel composition did not have a significant impact on operational stability or pollutant emissions. The CO and NO_X emissions were consistently low during the tests.

5. MGT VALIDATION TESTS

The objective of the final phase of the research project presented in this work was to investigate the applicability of the COSTAIR burner system in an operational micro gas turbine. Points of interest were stability of combustion, pollutant emissions and also how the system would respond to changes in fuel quality, a crucial issue for decentralized applications using locally available fuel gases.

Therefore, the COSTAIR burner system was mounted into a micro gas turbine which is installed at Fraunhofer UMSICHT.

Originally, this MGT, a turbec MGT T100, was intended to operate with natural gas which is why extensive adjustments to the instrumentation and control equipment were necessary in order to use low calorific fuel gases. Furthermore, the piping and the valves had to be refitted accordingly. A detailed overview of these activities is presented in in [4, 5, 6].

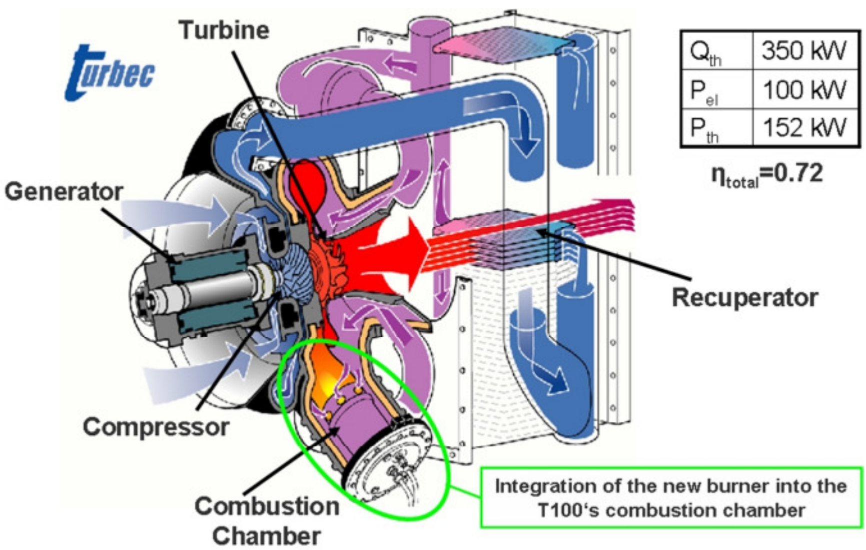

Figure 6: Schematic of the turbec MGT T100

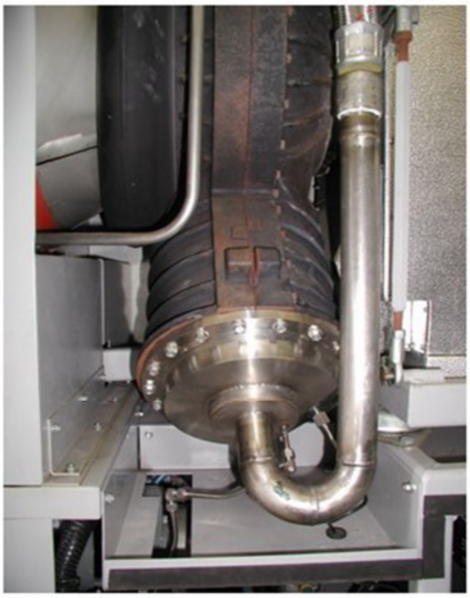

Figure 7: COSTAIR Burner Mounted in the MGT

Figure 6 shows a schematic of the MGT T100, while Figure 7 shows the installed COSTAIR burner (including the head pipe) in the micro gas turbine.

The flexibility of the burner and the response of the MGT system as a whole on changing fuel qualities were tested for several different lean gas qualities. As there was no gas mixing facility available at UMSICHT; the gas mixtures were created by diluting natural gas with nitrogen. The natural gas was extracted from the local gas distribution network, while a mobile trailer supplied the nitrogen.

An overview of the gas mixtures used during the validation tests and their corresponding LCV is given in Table 2.

The individual validation tests were conducted according to following procedure:

Table 2. Tested Low Calorific Fuel Gases

Experiment No.	CH_4 content [vol-%]	LCV [kWh/Nm^3]
1	26.5	2.485
2	19.5	1.829
3	18.5	1.542
4	14.0	1.313

First the set points of the turbine’s air ratio controller were adjusted for each gas mixture. Next, the turbine’s start up frequency was selected to meet the specifications of the validation tests. The ignition of the burner with natural gas occurred automatically. The main fuel gas line was opened manually by overriding the turbine’s control unit. Then the turbine was taken into operation and gradually powered up to a maximum electrical load of 100 kW_{el}. Once a point of steady operation was reached, the exhaust gases were analyzed periodically throughout a 1 hour interval. Afterwards, the gas valve leading to the pilot burner was shut and an additional exhaust gas analysis was recorded for another 1 hour period. Finally, the MGT was shut down and the same procedure was repeated for the other gas compositions.

Figure 8 shows the MGT’s electrical output, positioning of the main fuel gas valve, pilot burner valve and exhaust gas temperature during the validation tests. The dotted vertical lines denote the time periods when the pilot burner was switched off. It can be seen that the MGT control system responds well to changing fuel qualities, providing a constant electrical power output as well as constant flue gas temperatures. Also, it is possible to operate the system without a stabilising pilot burner.

Figure 9 illustrates the measured NO_X- und CO-emissions as functions of the CH_4 content in the fuel gas. The graph shows that low calorific fuel gases with methane contents as low as 12.5 vol-% result in single digit NO_X emissions. However, if the CH_4-content is decreased any further, the CO emissions rise exponentially. Increased CO emissions are strong indicators for an incomplete combustion process which may cause flame instabilities. In general, the NO_X emissions show a linear dependency of the methane content.

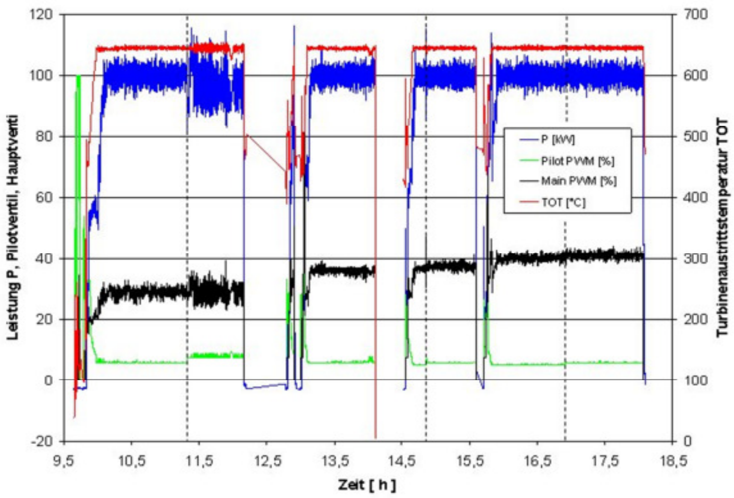

Figure 8: Electrical Output, Gas Valve Positions and Flue Gas Temperatures during Validation Testing

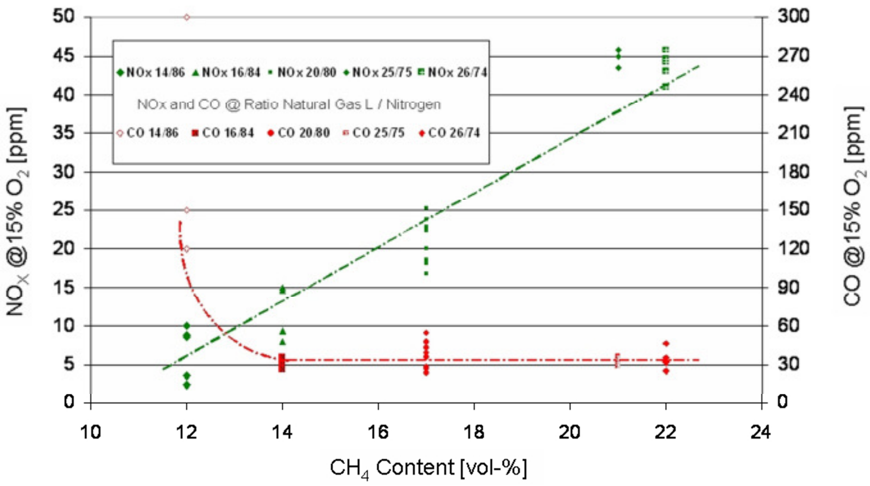

Figure 9: CO and NO_X Emissions as Functions of the CH_4 Content

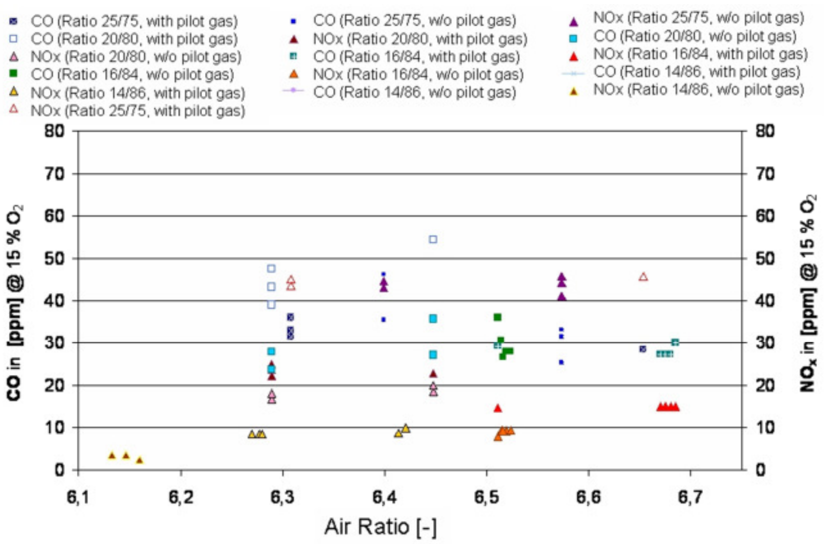

Figure 10: CO and NO_X Emissions as Functions of the Air Ratio

The optimum operating range for the MGT is reached when the fuel gas contains 13-20 vol-% CH_4 where low CO and NO_X emissions can be found.

Figure 10 shows the dependencies between emissions and air ratios as well as the influence of the pilot burner. Generally speaking, both CO and NO_X emissions were found to be low over the entire range of air ratios. Also, switching off the pilot burners tends to decrease emissions even further without impairing combustion stability.

6. CONCLUSION

In the course of the project presented here, the applicability of the COSTAIR burner system for the use of low calorific gases in a micro gas turbine was investigated.

In a first step, the burner system was adapted and optimized for the use of low calorific gases. The influence of different fuel gas compositions and properties was investigated in atmospheric experiments.

In the second phase, GWI's atmospheric test rig was moved to an operational landfill site and fuelled with the locally available, untreated landfill gas during three weeks of continuous operation. During that time, both stable combustion and low CO and NO_X emissions were observed.

In the final step, the burner system was installed in an MGT to be tested under typical operating conditions. It was found that the MGT system responded well to different fuel gas compositions and maintained low emissions over a wide range of operating points.

The results of this research project show that the combination of the COSTAIR burner system and a micro gas turbine is an interesting solution for the use of low calorific gases for small scale decentralized power and heat generation. Even gases with very low methane contents can be successfully utilized.

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