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Micro Gas Turbine Operation with Biomass Producer Gas and Mixtures of Biomass Producer Gas and Natural Gas

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We report the performance of a standard commercial micro gas turbine on biomass producer gas and mixtures of biomass producer gas with natural gas. The micro gas turbine delivers full power on gas mixtures with a net heating value of at least 15 MJ/Nm^3. For gas of lower heating value, the maximum fuel gas flow limits the attainable power. At reduced power, the lower limit for stable operation is a net heating value of about 8 MJ/Nm^3. The gross efficiency of the micro gas turbine depends on output power but not on the gas heating value, within our measurement accuracy. Above 70% of full power, emissions of CO, unburned hydrocarbons and NO are over 200 times, 15 times and 3 times lower than those of a gas engine of similar size. At part load below 70% of full power, the micro gas turbine burner switches to a different operating mode which produces higher CO and NO levels. The CO emission remains far below that of a gas engine, the NO emission becomes similar.

Introduction

In response to growing concerns about the climate effects of burning fossil fuels, biomass is receiving a lot of attention and political support as an alternative fuel. Much effort is spent on increasing the use of locally available biomass in small-scale installations for co-generation of heat and power (CHP). Most of these installations rely on gas engines and operate on biogas, produced by digestion of wet biomass, or on biomass producer gas, produced by gasification of dry biomass.

A disadvantage of gas engines is the emission of NO_x and unburned or partly burned fuel. The emission of NO_x can be and has been reduced by primary measures which reduce the combustion temperature. However, the amount of unburned fuel, typically 0.5% to 1%, tends to be increased by these NO_x reduction measures. Catalytic exhaust gas treatment, common with natural gas fired engines, is hampered, in case of biomass derived gas, by the presence of trace compounds which poison the catalyst.

Instead of gas engines, micro or mini gas turbines may be used. These realize complete combustion of fuel with significantly lower NO_x emissions. Unfortunately, that advantage is offset by lower electrical efficiency. To an operator, the lower electrical output causes a loss of income which usually cannot be compensated by higher income from heat delivery or lower operating costs.

Market opportunities may arise if strict emission limits have to be obeyed or if cleaner exhaust gas has an economical value. The latter would be the case if exhaust gas could be used for CO_2 addition to greenhouses to enhance productivity.

ECN, Cogen Projects, HoSt and Pon Power have performed a study on the technical performance of a micro gas turbine operating on biomass producer gas and on the economical prospects of that concept for CHP.

Here, we present results from experiments with a standard Capstone 30 kW$_e$ micro gas turbine operating on biomass producer gas and mixtures of biomass producer gas with natural gas. Some of these results were presented in May 2007 at the 15th European Biomass Conference and Exhibition in Berlin[1]. A full report (in Dutch) on the experiments and economical analysis can be obtained from the ECN website[2].

Experimental Lay-Out and Procedures

The installation used for the production of clean biomass producer gas consists of a 500 kW$_{th}$ circulating fluidized bed (CFB) gasifier, a gas cooler, and gas cleaning comprising dust, tar, water and NH_3 removal. The air-blown CFB gasifier operates near atmospheric pressure at about 850°C. The gas is cooled to 400°C before dust is removed by a cyclone. Tar is removed by the OLGA oil scrubber system developed by ECN[3] and marketed by Dahlman[4]. A water scrubber removes NH_3 and reduces the water content to the water vapor pressure near the temperature of the surroundings (about

[1] Rabou, L.P.L.M.; Grift, J.M.; Conradie, R.E.; Fransen, S.; Verhoeff, F.: *Proc. 15th European Biomass Conference and Exhibition, Berlin, 2007, contribution V2.1.I.6.* Report ECN-M-07-073.

[2] Rabou, L.P.L.M.; Grift, J.M.; Conradie, R.E.; Fransen, S.: *Report ECN-E--06-026*, available at www.ecn.nl/publicaties (i.e. select Dutch version of website).

[3] Bergman, P.C.A.; Paasen, S.V.B. van; Boerrigter, H. In: *Pyrolysis and Gasification of Biomass and Waste*, A.V. Bridgewater (ed), CPL press, Newbury, United Kingdom, 2003, 347 - 356.

[4] See page "products" at www.dahlman.nl.

15°C). During the present experiments, clean wood pellets were used as fuel.

Part of the clean producer gas is used in a gas engine or micro gas turbine, the remainder is burned in a modified natural gas boiler. Results presented here for the micro gas turbine were obtained in the course of a 700 hours performance test of the gasifier, gas cleaning and gas engine. A more extensive description of the installation and results of the endurance test can be found in another contribution to the 15th European Biomass Conference and Exhibition[5] and in an article to be published[6].

Table 1 shows the average composition of the clean producer gas during the micro gas turbine tests. The gas has a net calorific value of about 6 MJ/Nm^3. Over periods of hours or days variations around the average composition of 0.5 to 1 vol.% are observed for CH_4, H_2 and CO_2 and up to 2 vol.% for CO and N_2. These variations are caused by differences in moisture content of fuel batches, the filling degree of the fuel bunker and gradual changes in the operating temperature. Short term fluctuations of 0.1 to 0.2 vol.% reflect the sensitivity of the CFB gasification process to irregularities in the fuel feed rate.

Table 1: Composition (volume %) of producer gas during micro gas turbine tests.

Component	Average	Minimum	Maximum
CO	16.9	14.9	19.3
H_2	6.9	6.1	7.3
CH_4	4.2	3.7	4.5
N_2	52.0	50.4	54.6
Ar	0.62	0.61	0.64
CO_2	15.3	14.3	15.8
H_2O	1.8		
C_2H_4	1.7	1.4	1.9
C_2H_2	0.23	0.17	0.34
C_2H_6	0.09	0.05	0.13
C_6H_6	0.23	0.21	0.26
C_7H_8	0.017	0.013	0.022
tar			<0.002

Capstone micro gas turbines are available in 30 kW$_e$ and 65 kW$_e$ size in versions for natural gas and for landfill gas or biogas. We used a standard 30 kW$_e$ natural gas version. Only one software parameter, the fuel index, was changed to manage the lower calorific value of producer gas. The Capstone operating system selects the turbine speed and temperature to match the required power output, and regulates the fuel gas valve accordingly.

At the test site, Dutch natural gas of 31.7 MJ/Nm^3 (i.e. Groningen gas quality) is available at 100 mbar and producer gas at 70 mbar above atmospheric pressure. Both gas lines are connected to the gas compressor which is needed to obtain the required micro gas turbine entrance pressure of about 4 bar. A back pressure valve prevents the higher pressure natural gas from entering the producer gas line. Safety valves in the natural gas and producer gas lines switch off the gas supply when CO or H_2 is detected in the room where the micro gas turbine is situated.

For ease of operation, we start the micro gas turbine with natural gas. When operating conditions are stable, we gradually replace natural gas by producer gas. To that end, we reduce the opening of a valve in the natural gas line. Thus we reduce the pressure in the natural gas line downstream of the valve until the back pressure valve in the producer gas line opens. From that point, the gas compressor receives a mixture of natural gas and producer gas. Further reduction of the valve opening in the natural gas line increases the producer gas content in the gas mixture.

In response to the lower calorific value of the gas mixture, the micro gas turbine operating system increases the opening of the fuel gas valve to allow a larger fuel gas flow to the burner. The operating system also decreases the air flow by a slight reduction of the turbine speed. The maximum allowable producer gas content in the fuel gas mixture is reached when the fuel gas valve is fully opened or when combustion becomes unstable. For measurements requiring prolonged operation, we add slightly more natural gas than the minimum needed, in order to retain a control margin for the operating system.

The composition of producer gas and exhaust gas is monitored continuously and recorded automatically each minute. The natural gas flow is measured by a standard rotary meter, the producer gas flow by a turbine gas meter. Typically, these gas meters are accurate within 0.5%. However, as they are used at the lower limit of their operating range, larger deviations may occur. The recorded values are corrected to the normal volume at standard pressure and temperature.

Power output delivered to the grid, engine speed, turbine temperature and fuel gas valve position are read from the micro gas turbine operating console and recorded manually. The micro gas turbine efficiency is calculated from the power output, and the natural gas and producer gas flows multiplied by their respective net heating values. In case of producer gas, the net heating value is calculated using the measured producer gas composition. We estimate our results to be accurate within a 2% relative error margin.

Results

When producer gas is added to natural gas, the fuel gas valve opens wider in response to the lower heating value of the fuel gas mixture. The maximum opening of the fuel gas valve is reached when the operating console indicates a value of 80%. At full power and full opening of the fuel gas valve, the fuel gas mixture contains 65% producer gas by volume. At that point, the producer gas contributes only 26% to the mixture's net heating value of 15 MJ/Nm^3. In fact, full power with this producer gas mixture is a few percent below the 30 kW$_e$ output with pure natural gas, as the turbine speed is reduced to match the increased fuel gas flow by a smaller air flow.

According to our measurements, the gross electrical efficiency of the micro gas turbine at full power remains approximately 26% when producer gas is added to natural gas. However, more energy is needed to compress the larger volume of fuel gas. Based on data supplied for natural gas compression, we expect the

[5] Verhoeff, F.; Rabou, L.P.L.M.; Paasen, S.V.B. van; Emmen, F.; Buwalda, R.A.;Klein Teeselink, H.: *Proc. 15th European Biomass Conference and Exhibition, Berlin, 2007, contribution OA7.5*.

[6] Verhoeff, F. et al, to be published.

approximate doubling of the fuel gas volume to result in about 1% additional loss of net electrical efficiency.

If producer gas were available of higher calorific value, a larger contribution could be realized. An indirect gasifier, using e.g. the SilvaGas process developed at Battelle (USA), the FICFB process developed by the Technical University Vienna and applied in Güssing (Austria), or the Milena process in development at ECN, would allow to reach full power with 100% producer gas.

With the producer gas actually available at ECN from the direct air-blown CFB gasifier, a larger contribution from producer gas at full power would require hardware modifications of the micro gas turbine to increase the fuel gas flow. Instead, we investigated the performance with larger producer gas contributions at part load. This is not an economical proposition, but serves to show that the operating range can be extended to fuel gas of much lower heating value than indicated by the technical specifications of the micro gas turbine. Moreover, it allows us to evaluate emissions for operation on producer gas.

Figure 1 shows the maximum producer gas contribution to the fuel gas input, by volume and energy, at full and part load operation. Multiple results at 10, 15 and 20 kW_e show the effect of varying producer gas quality. During all our measurements, the concentration of unburned hydrocarbons remained about 5 ppmV. This corresponds to about 0.05 vol% of the fuel gas slipping through the micro gas turbine combustion system.

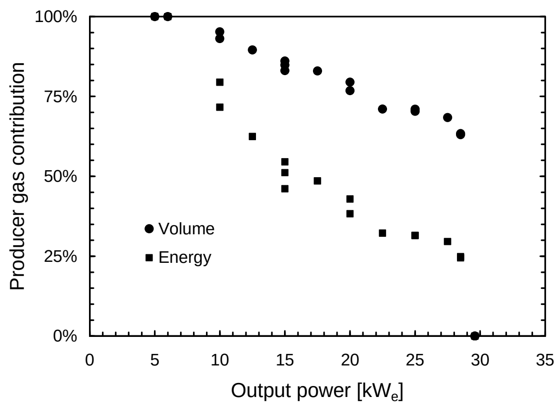

Figure 1: Maximum contribution of producer gas, by volume and energy, to micro gas turbine fuel gas input as function of output power.

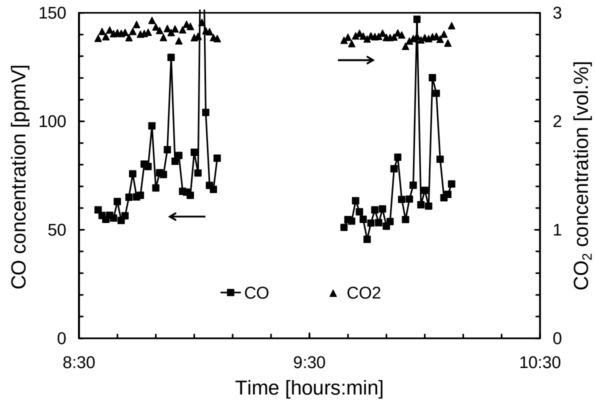

Figure 2: CO and CO_2 concentration in dry exhaust gas from micro gas turbine during operation at 5 kW_e with 100% producer gas. Data of second test shifted in time to match axis.

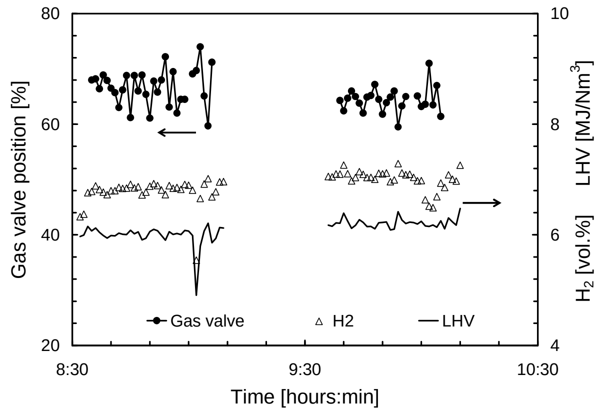

Figure 3: H_2 concentration and net heating value (LHV) of producer gas, and fuel gas valve position of micro gas turbine during operation at 5 kW_e with only producer gas.

Figures 2 and 3 show results of operation with only producer gas at 5 kW_e. Although the net heating value of 6 MJ/Nm^3 allows operation for short periods, peaks in the exhaust gas CO concentration show the combustion to be unstable. The exhaust gas CO_2 concentration is 2.5 times the value for operation on natural gas at the same power output.

Changes in the fuel gas valve position correlate to changes in the producer gas heating value or H_2 content, but are comparatively large. Peaks in the CO emission, near the end of each of the two periods shown, are accompanied by clearly audible booming noises. Both are probably caused by flame blow-off and reignition. The combustion instability may partly be to blame on the nervousness of the fuel gas valve regulation. Capstone has recognized that as a more general problem and replaced the fuel gas valve in recent products by a different type with more stable behavior.

According to our measurements, the gross electrical efficiency at 5 kW_e is 14%. It should be taken into account, however, that the micro gas turbine is operating at only $1/6^{th}$ of its design power output.

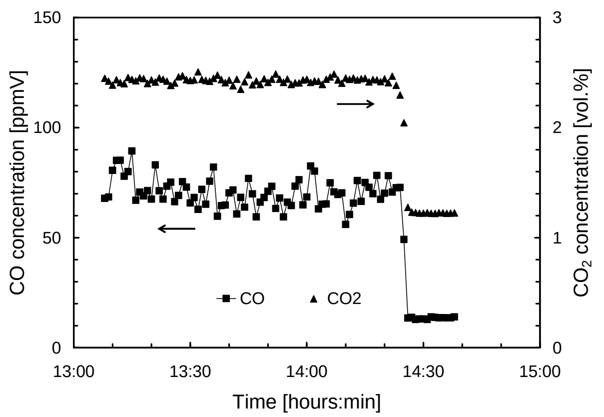

Figure 4: CO and CO_2 concentration in dry exhaust gas from micro gas turbine during operation at 7.5 kW_e with a mixture of 93 vol.% producer gas and 7 vol.% natural gas. From 14^h25 are for operation with 100% natural gas.

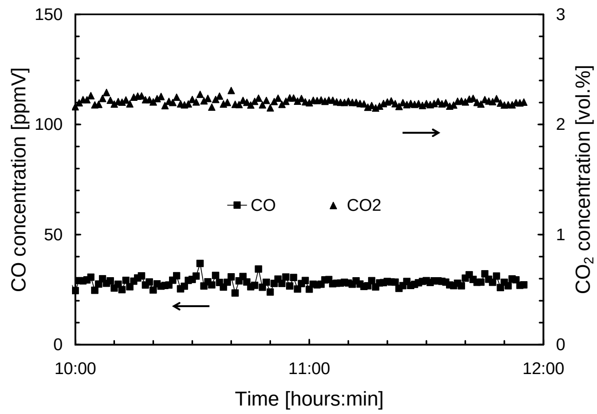

Figure 5: CO and CO_2 concentration in dry exhaust gas from micro gas turbine during operation at 15 kW_e with a mixture of 80 vol.% producer gas and 20 vol.% natural gas.

Figure 4 shows results of operation at 7.5 kW_e with a mixture of 93% producer gas and 7% natural gas by volume (72% and 28% by energy). The fuel gas mixture has an average net heating value of 8 MJ/Nm^3. The limited increase in heating value makes the combustion stable enough to prevent audible signs of flame blow-off and reignition, but fluctuations in the exhaust gas CO concentration indicate the combustion still to be at the edge of instability.

The exhaust gas CO_2 concentration is lower than for operation with only producer gas because of the dilution by natural gas, which produces almost 4 times as much exhaust gas per volume of fuel gas. Data for operation with only natural gas show the exhaust gas CO and CO_2 concentrations to be 5 times and 2 times lower than with nearly 100% producer gas. The larger factor for CO indicates that some CO may be due to unburned fuel. To explain the difference, 0.5% would have to slip through, i.e. substantially more than derived from the amount of unburned hydrocarbons. More likely, the additional CO is due to a shorter residence time or lower temperature in the combustion zone.

Within the accuracy of our measurements, the gross electrical efficiency at 7.5 kW_e is 17% both with only natural gas and with nearly 100% producer gas.

Figure 5 shows results of operation at 15 kW_e with a mixture of 80% producer gas and 20% natural gas by volume (43% and 57% by energy). The fuel gas mixture has an average net heating value of 11 MJ/Nm^3. Clearly, the exhaust gas CO concentration is more stable than at 7.5 kW_e with a lower calorific gas mixture. The average exhaust gas CO concentration is about 2 times lower than at 7.5 kW_e, but the same holds true for operation with 100% natural gas at these power outputs. The exhaust gas CO_2 concentration is lower again because of further dilution by natural gas.

The gross electrical efficiency at 15 kW_e is about 22% and again not affected by the use of a mixture with producer gas instead of only natural gas.

Above about 20 kW_e, the micro gas turbine operating system switches to a low-NO combustion mode, which reduces thermal NO formation. Figure 6 shows the effect of the switch on NO emission to be smaller for mixtures of producer gas and natural gas than for 100% natural gas. Below 20 kW_e, the lower NO emissions for operation with producer gas mixtures point to lower combustion temperatures than with natural gas. That agrees with the explanation given above for the higher CO emissions with producer gas mixtures. In low-NO combustion mode above 20 kW_e, NO emissions for operation with producer gas mixtures are slightly higher than with 100% natural gas. That may indicate thermal NO suppression to be less efficient at high fuel flow, but more likely is due to the combustion of some residual NH_3 in the producer gas.

The switch to low-NO combustion mode reduces the CO concentration for operation with mixtures of producer gas and natural gas to the level observed with 100% natural gas (see Figure 7). Apparently, the high-power combustion mode effectively prevents cold zones where CO oxidation is slow. As part load operation below 70% of maximum power would be avoided for economical reasons, it is fair to say the use of producer gas instead of natural gas does not increase the CO emission in practical operation conditions.

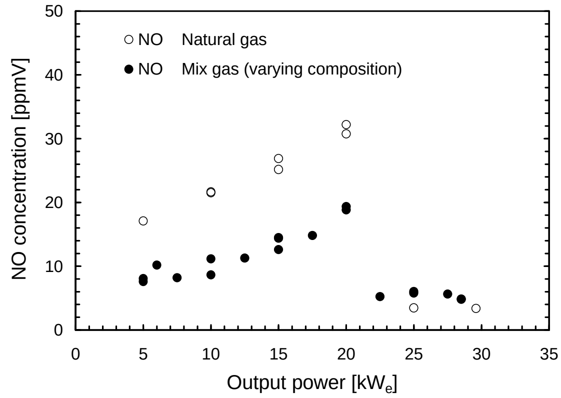

Figure 6: NO concentration in dry exhaust gas of micro gas turbine as function of output power for operation on biomass producer gas mixed with varying amounts of natural gas and on 100% natural gas.

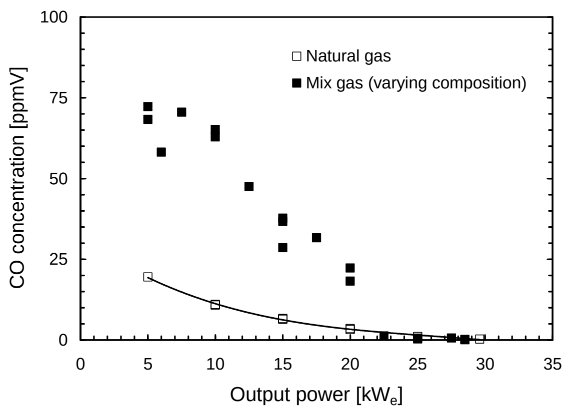

Figure 7: CO concentration in dry exhaust gas of micro gas turbine as function of output power for operation on biomass producer gas mixed with varying amounts of natural gas and on 100% natural gas.

The above data for emissions are given as measured in dry exhaust gas. For comparison with data for a gas engine, the present results must be corrected in order to compensate for the higher dilution by excess air in case of a micro gas turbine. Correction to 6% O_2 in dry exhaust gas increases the concentrations by a factor 5. Above 20 kW_e, the result would become less than 5 ppm CO, 25 ppm unburned hydrocarbons and 30 ppm NO. For comparison, our results for a 45 kW_e gas engine operating on the same producer gas are: more than 1000 ppm CO, 350 ppm unburned hydrocarbons and 70 to 100 ppm NO.

Conclusions

The standard Capstone micro gas turbine operates remarkably well on mixtures of biomass producer gas and natural gas. Even without modifications it is able to deliver full power provided the net heating value is at least 15 MJ/Nm^3. Hence, the Capstone micro gas turbine should be able to deliver full output power on producer gas from indirect gasifiers.

The lower net heating value of producer gas, as compared to natural gas, has a negligible effect on the gross electrical efficiency of the Capstone micro gas turbine. The net electrical efficiency will decrease by about 1% for producer gas from an indirect gasifier because of the higher power demand for compression of the larger fuel gas volume.

Our part load results show, it might suffice to enable a larger fuel gas flow to allow full power operation with even lower calorific gas, down to a net heating value of 8 MJ/Nm^3. However, the even larger fuel gas flow would lead to a further reduction of the net electrical efficiency.

Above 70% of design power output, emissions of CO, unburned hydrocarbons and NO are very low, both for pure natural gas and mixtures with biomass producer gas. When compared to a gas engine of similar size, the micro gas turbine produces over 200 times less CO, 15 times less unburned hydrocarbons and 3 times less NO. At part load below 70% of full power, the micro gas turbine burner switches to a different operating mode which produces more CO and NO. The NO emission then becomes similar to that of a gas engine, but the CO emission remains far lower.

If instead of natural gas producer gas could be used, with the same composition as in our experiments, the CO_2 concentration of the exhaust gases would increase by a factor 2.5. The higher CO_2 concentration would be advantageous, if the exhaust gases were used in a greenhouse to enhance production. If producer gas from an indirect gasifier were used, in which the gasification process is separated from the combustion for process heat requirements, the CO_2 concentration would increase only by a factor 1.7. However, operation on producer gas from an indirect gasifier would be possible without modifications to the micro gas turbine and require less energy for fuel gas compression.

Acknowledgment

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