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FORD VSG 411
FUELED BY PRODUCER GAS FROM A TWO-STAGE GASIFIER

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ABSTRACT: Experiments have been carried out with a Ford VSG 411 SI engine in conjunction with a two-stage gasifier with a nominal thermal input of 100 kW. The fuel gas is produced from wood chips.

The engine experiments showed that the knocking resistance of the producer gas was good, and the producer gas showed excellent lean burn abilities. The measured NO_x emissions from the engine were very low: only at λ~1.3 or lower did the NO_x emissions reach a value that was higher than the given limit for NO_x emissions in Denmark*. On the other hand, for all values of λ>1.3, the measured CO emissions were higher than the given limit for CO emissions in Denmark* [1]. Investigations into the problem of backfiring were carried out. Several possible causes of backfiring were examined, and the problem was eliminated.

It was shown that the producer gas has a power/efficiency advantage compared to natural gas when operating the engine at part load conditions (lean burn).

Several inspections of the internal parts of the engine showed no sign of extraordinary engine wear or deposits, due to the use of producer gas as fuel for the engine.

The main conclusion of the engine experiments is that the producer gas from the DTU two-stage gasifier is a very good alternative fuel for stationary SI engines when utilised for heat and power production.

INTRODUCTION

The Department of Energy Engineering at the Technical University of Denmark has been doing extensive research into thermal gasification of biomass during the last decade. One of the main activities has been the research and development of the two-stage gasification principle. A connective activity has been the investigation into the utilisation of the producer gas as a fuel for stationary SI gas engines in heat and power production. This paper presents results from this work.

1. THE GASIFIER

The gasifier has a horizontal, externally heated, combined drying and pyrolysis unit and a vertical gasification reactor. The produced gas is cleaned by a cyclone, a bag filter and a paper filter in conjunction. Nominal thermal input for the gasifier is 100 kW, it has been tested on wood chips and SGF briquettes. The two-stage gasifier is characterised by a very low tar level in the raw gas and a high thermal efficiency.

The following are examples of data from gas produced from wood chips at full load conditions [2]:
Raw gas: particles ~500 mg/Nm^3, tar ~50 mg/Nm^3.
Filtered gas: particles ~10 mg/Nm^3, tar ~0 mg/Nm^3.
Thermal efficiency: ~90 % based on lower heating value.

The engine utilises around 50 % of the gas and the rest is burned by a gas burner. The gas condition at the inlet of the engine is around 100 % moist, with a pressure of 30 mm H_2O (rel) and a temperature of 45 °C. A typical gas composition could be (in dry volume percents): H_2: 34; N_2: 31; CO:18; CO_2:15.5 and CH_4: 1.5, with a lower heating value of 6.6 MJ/Nm^3 and a stoichiometric air/fuel ratio of 1.4.

2. TEST ENGINE SET-UP

The test engine is a, Ford VSG 411 1.1 litre natural aspirated four cylinder 4-stroke industrial SI engine with a modified intake system. A gas/water heat exchanger is placed on the exhaust system, which makes it possible to measure the energy content of the exhaust gas by measuring water flow and inlet/outlet temperatures. At the end of the exhaust pipe a valve is placed, which enables variation of the back-pressures. The engine is coupled to an

* As of the 17th of October 1998, the emission limits for NO_x and CO in Denmark are 650 mg/Nm^3

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eddy current brake, which make it possible to vary the load and rotating speed in order to test various operating conditions. Power and efficiency is measured at the crankshaft and a lower heating value is used for the energy-input measurements. Air and gas flow is measured.

The composition of the producer gas is measured continuously. Hydrogen content is measured by a thermal conductivity analyser, CO, CO_2, CH_4 and oxygen are all measured by IR instruments. The rest is assumed to be nitrogen. The exhaust gasses are also tested continuously: CO, O_2, NO and NO_2 by chemical cells. All engine data except pressures and airflow are continuously recorded on a PC based data acquisition system.

On January 1st 2000 the engine had been operating approximately 130 hours on natural gas, 145 hours on real producer gas and 25 hours on synthetic producer gas. Figure 1 shows the test engine set-up.

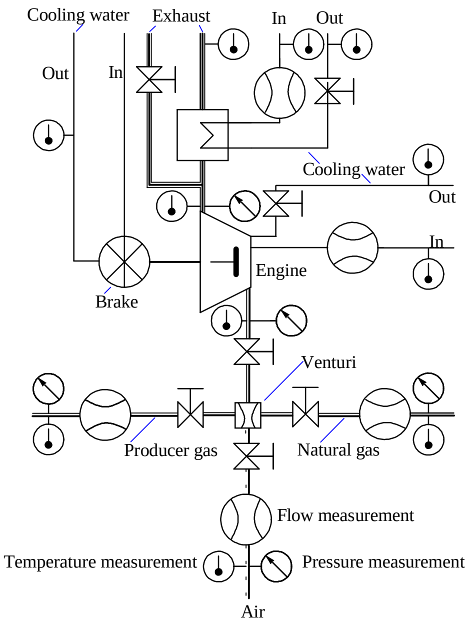

Figure 1. Test engine set-up

3 BACKFIRE

Due to the high hydrogen content of the gas from the two-stage gasifier severe problems with backfiring from the engine has occurred. During backfire, the gas/air mixture in the intake manifold ignites in an explosive manner, causing the engine to stop. Backfiring mostly occurred during high engine loads. Therefore during stoichiometric combustion conditions, it was necessary to throttle the manifold pressure lower than -0.25 bar(rel) and in unthrottled conditions (manifold pressure ~ -0.006 bar(rel)) to keep lambda higher than 2 for trouble free operation. Several possible causes of backfiring have been examined:

-Glowing particles in the fuel gas. This has been tested with synthetic producer gas, which is totally free of particles, and by using extra filters on the real producer gas. Both running conditions gave approximately the same backfire problems as experienced when running on normal untreated producer gas. Therefore it did not seem likely that the particles were causing the problems.

-Back flow of exhaust gasses. Back flow happens when the inlet and the outlet valves are open at the same time. This was tested by raising the exhaust pressure to 0.3 bar (rel). This did not make any change to the backfire occurrence, and this theory was thus also eliminated.

-Hot spots in the combustion chamber. Hot spots in a combustion chamber would normally be: the tip of the spark plug, the exhaust valve and protruding points and corners. To test the "hot spot theory" spark plug with different thermal conductivity were tested. These tests gave some rather unexpected results, since the rate of backfire was higher when "cold" spark plugs were used instead of the "warmer" spark plugs. This was the exact opposite reaction than expected. The problems therefore seemed to occur from the spark plugs, but not because of hot spots.

-Flame ionisation. The significant influence of the spark plugs indicated that backfire was influenced by the ignition system. Kondo [3] conducted experiments with a hydrogen fueled engine and experienced abnormal ignitions occurring in different parts of the engine cycle. If the abnormal ignition took place during the intake stroke, it resulted in backfire. The abnormal ignition was caused by the low ionisation of a hydrogen/oxygen flame compared to a hydrocarbon/oxygen flame. This means that there will be a large amount of residual electric energy in the spark plug cables after each ignition. This energy can be released by a pressure drop in the cylinder or by induction caused by ignition in another cylinder with a close lying ignition cable. In order to avoid the latter phenomenon, the ignition cables for the test engine were shielded, and the new set-up was tested on synthetic producer gas. The effect was significant, only extreme ignition timing could now provoke backfiring. At all normal operating conditions, the engine was perfectly stable.

The experiments referred to in this paper are all done after the backfire problem was solved.

4 EXPERIMENTS

Due to limited operating time with the two-stage gasifier (the gasifier is only operating approximate four times a year, each time for one week), some of the tests are carried out on producer gas made from clean gasses stored in high pressure bottles. By using synthetic producer gas, the engine can be tested independently of the gasifier and with a more stable gas composition. The drawback of this method is that any effects occurring from the presence of particles, tar and water are neglected. Because of the low content of particles and tar in the gas from the two-stage gasifier, it is probably only the lack of water (7-8 %vol.) that has a major influence on the engine measurements. This means that the NO_x content measured in the experiments with the synthetic gas probably will be slightly higher than what would be the case with the real producer gas. Due to the lack of water in the synthetic gas, there will be a difference in heating value and stoichiometric air/fuel ratio, which means that the synthetic producer gas will have a slightly higher power output and efficiency than the real producer gas. However this is partly compensated in the real producer gas, by better cylinder filling due to the cooling effect from the water.

Due to the high hydrogen content, extensive problems with knocking could also be expected. For gaseous fuels, the

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methane number is used to compare knocking tendencies for different fuels, like the octane number for liquid fuels. The methane number is defined from methane and hydrogen, with methane numbers of 100 and 0 for the clean gasses. Danish natural gas has a methane number around 70, according to Danish Gas Technology Centre, the institution that makes the official analysis on the Danish natural gas. Various algorithms have been developed to calculate methane numbers for multi-component gaseous fuels. For the two-stage producer gas, the methane number has been calculated to be around 50, which means that the theoretical knocking tendency should be rather high. The test engine has a compression ratio of 9.5:1. Even at full load, low speed and with very advanced ignition, knocking did not occur. Experiments conducted on single cylinder 0.5 litre, 4 stroke test engine with a compression ratio of 12.5:1 [4] operating on synthetic producer gas, did not give any problems either. It seems likely that the knocking tendency for two-stage producer gas is smaller than that for Danish natural gas. Further investigations concerning the knocking limit of producer gas are planned.

Due to the low heating value of the producer gas, the power output and the efficiency of the engine will decrease, when compared to operation on natural gas. This is partly compensated for by the higher stoichiometric fuel/air ratio of the producer gas. Totally the energy input to the engine will decrease with 5-15 percent, depending on the gas composition and the relative air/fuel ratio, lambda (λ).

The experiments with synthetic producer gas were conducted at a constant speed of 1500 rpm. For real producer gas, the speed was 2250 rpm. Before every measurement the ignition timing was adjusted to give maximum brake torque (MBT), and the engine was always operated at full open throttle (FOT). The load was changed by varying the amount of fuel fed to the engine and thus λ.

Figure 2 shows the power and efficiency of synthetic producer gas and natural gas depicted as a function of λ. At λ<1.4 the natural gas has the highest efficiency and power output, but after λ~1.4 power and efficiency drops off and at λ~1.7 the engine dies. The power curve for the synthetic producer gas on the other hand is close to linear and goes to zero for λ>3. This power curve gives a very flat parabolic efficiency curve with a maximum at λ~2. The efficiency is lower than for natural gas until λ~1.6 after which the producer gas takes over. Figure 5 shows measurements of power and efficiency for real producer gas from the DTU two-stage gasifier, and again the same pattern as for synthetic producer gas is seen. The efficiency of the engine, when running on producer gas, gets as high as for natural gas, which is due to a favourable gas composition. The power and efficiency graphs show that producer gas is an excellent lean burn fuel.

Figure 3 shows NO_x and CO emissions of the engine when running on synthetic producer gas and natural gas. The limit for NO_x and CO emissions from gas engines in Denmark is 650 mg/Nm^3.

CO emissions from the engine when running on synthetic producer gas are quite high especially at lean conditions. This is due to the high content of CO in the fuel and therefore, like UHC emissions from natural gas engines, a measure of fuel passing unburned through the combustion. At conditions richer than λ~1.3, the CO emissions are below the limit; at leaner conditions the emissions extend the limit significantly.

For λ>1.4 it is not a problem to get below the limit for NO_x, but at richer conditions the emissions get above the limit. Experiments with synthetic producer gas has shown that it is possible to lower the NO_x emissions at rich conditions considerable by advancing the ignition timing compered to MBT (see Figure 4). It is possible to get below the limit without derating the engine significantly.

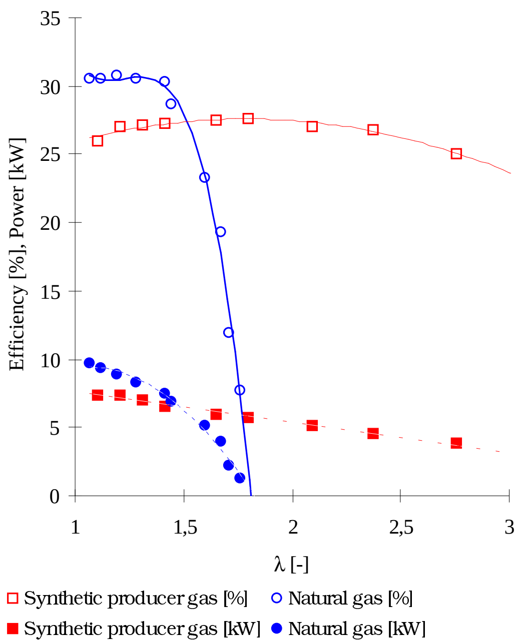

Figure 2. The power and efficiency of synthetic producer gas and natural gas depicted as a function of λ at 1500 rpm, FOT and MBT

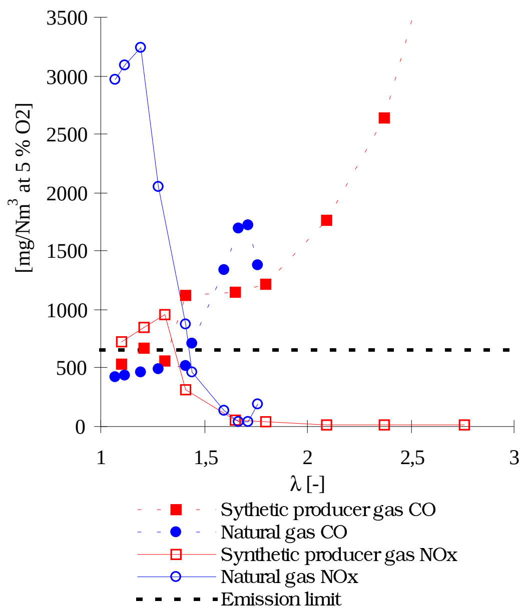

Figure 3. NO_x and CO emissions of synthetic producer gas and natural gas depicted as a function of λ at 1500 rpm, FOT and MBT

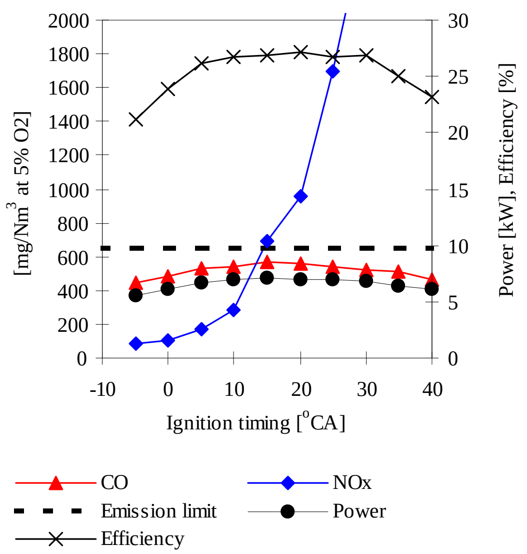

Figure 4. Power, efficiency, and emissions depicted as a function of the ignitions timing at 1500 rpm, FOT and λ~1.3

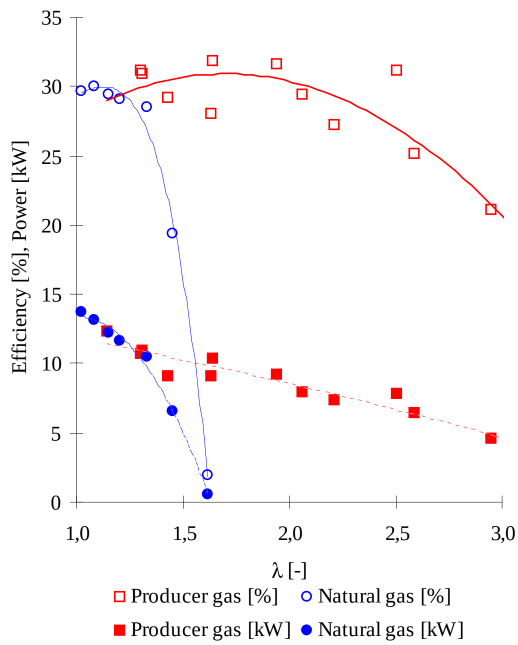

Figure 5. The power and efficiency of producer gas and natural gas depicted as a function of λ at 2250 rpm, FOT, and MBT

5. INSPECTION OF ENGINE

After all major test sessions, the combustion chamber was inspected. This was done either by removal of the cylinder head or by using an endoscope, inserted through the spark plug hole. None of the checks revealed any indications of tar or particles, which is normally the main problem for producer gas engines. The order of deposits on the top of the piston, cylinder top, valves and cylinder head, was the same for producer gas as for natural gas. Superficial corrosion could be seen after a few days of no operation. It was not possible to see or measure any engine wear.

Analysis of the engine lubricant showed that the only abnormal results were slightly increased amounts of Fe, Cu and Al

Overall the engine was not affected by the producer gas more than the natural gas, except for the corrosion during periods of no operation. If the plant had operated continuously without engine stops, corrosion would probably not have been a problem either.

CONCLUSION

Backfire - Several possible reasons of backfiring were investigated. It was the relatively weak ionisation of the hydrogen/oxygen flame that caused the problems. Electric potentials in the ignition cables caused abnormal ignitions. Shielding of the ignition cables solved the problem.

Knocking - Extreme operating conditions were tested at compression ratios of 9.5:1 with the Ford VSG 411 and 12.5:1 with the 1 cylinder 0.5 litre BUKH engine without any knocking problems. It seems like two-stage producer gas has better knocking resistance than Danish natural gas.

Engine government - The ability of producer gas to operate with quality government of the engine has been proved. Through quality government it is possible to partly load the engine and still keep a high efficiency.

Emissions - Very low NO_x and high CO emissions were measured. The high level of CO is due to the high content of CO in the fuel and is therefore, like UHC emissions from natural gas engines, a measure of fuel passing unburned through the combustion.

Engine internals - No sign of engine deposits or engine wear. The engine oil is only slightly affected by producer gas.

The two-stage producer gas has proved to be a very good alternative fuel for stationary SI gas engines.

ACKNOWLEDGEMENTS

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