DTU

Characterization of biomass producer gas as fuel for stationary gas engines in combined heat and power production

Jesper Ahrenfeldt

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PREFACE

This thesis is written as a requirement to obtain a Ph.D. degree at the Technical University of Denmark. The work has been carried out during the period from July 1st 2001 to March 31st 2006. The supervisors were Associate Professor Jesper Schramm, and Associate Professor Ulrik Henriksen. Both are affiliated to the Energy Engineering Section at the Department of Mechanical Engineering.

Besides the main report this thesis consists of six appendices which include four peer reviewed scientific papers (**Appendix I**, **II, III, IV**), one conference paper without review (**Appendix V**) and a contribution to a book (**Appendix VI**). The report summarises the results from the papers and presents additional unpublished data.

The objective of the thesis is to obtain knowledge about the utilisation of producer gas from gasification of biomass as a fuel for stationary gas engines in heat and power production. This has been done by investigating and analysing the combustion process and engine-operating characteristics such as emissions, performance and efficiency. Data from three different gas engine based gasification plants as well as from lab-scale experiments is presented.

Report Chapter 1 describes the background and objective of the project.

In chapter 2 the small scale Viking biomass gasification test plant is described. The main part of the work carried out in this project is associated with this plant.

Chapter 3 presents two full scale gas engine based biomass gasification combined heat and power plants from which data is analysed.

In chapter 4 the properties of biomass producer gas is described. Examples of gas composition and properties from the different gasification plants are provided.

Performance characteristics for engine operation on biomass producer gas are described in chapter 5.

Measurements of emissions of CO, NO_x, UHC, PAH, aldehydes and N_2O are presented in chapter 6.

Chapter 7 provides an analysis of the combustion process for producer gas operation by applying a heat release model.

Effects of long term operation on biomass producer gas with regards to engine wear and deposits are presented in chapter 8.

Jesper Ahrenfeldt, 2007.

DANSK RESUME

Formålet med projektet har været karakteriseringen af forgasningsgas som motorbrændstof til stationere gasmotorer i kraft/varme-produktion.

Som en væsentlig del af projektet er der opnået mere end 3200 timers motordrift på forgasningsgas fra biomasseforgasningsanlægget kaldet "Viking". Anlægget er et demonstrations og forskningsanlæg opført på DTU i part som en del af nærværende projekt. Viking anlægget drives som et kraft/varme-anlæg og er fuldt automatiseret.

Sammensætningen af forgasningsgassen deriblandt indholdet af uønskede bestanddele er blevet undersøgt. På Viking anlægget var det ikke muligt at detektere nogle tjærestoffer eller partikler i gassen der går til motoren. I gassen fra to andre anlæg der er blevet undersøgt i projektet ses stadig væsentlige mængder af tjære og i særlige tilfælde giver tjære problemer, men generelt må det siges at tjære ikke er et problem for undersøgte anlæg. Ammoniak ses i væsentlige mængder i gassen fra to af de undersøgte anlæg og hvis den ikke fjernes kan ammoniakken bidrage til en betydelig NO_x emission fra motorerne.

Der er blevet udført en omfattende analyse af motordrift på forgasningsgassen. Måling af effekt, virkningsgrad og emissioner er blevet udført ved varierende last situationer fra 50% til 90% last. Det er vist at forgasningsgas er et fremragende "lean burn" brændstof, idet motordrift på en motor med sugedrift er mulig for $1.2 < \lambda < 2.8$ uden en væsentlig forringelse af virkningsgraden.

Ved motordrift på forgasningsgas ses generelt en betydelig emission af CO. Denne emission skyldes et slip af uforbrændt CO fra forgasningsgassen, og emissionen kan derfor sidestilles med emissionen af uforbrændte kulbrinter (UHC) fra motordrift på naturgas.

Da forgasningsgas er et fremragende lean brun brændstof er NO_x emissionen generelt ikke noget problem, men en høj koncentration af ammoniak i forgasningsgassen kan give problemer i nogle tilfælde.

Der blevet udført måling af emissionen af polycyclic aromatic hydrocarbons (PAH), aldehyder og lattergas ved motordrift på forgasningsgas. Målinger af PAH fra motorer på to anlæg har vist, at emissionen af PAH ikke er problematisk for motordrift på forgasningsgas og at der ikke er nogen sammenhæng mellem en høj emission af CO og en tilsvarende for PAH. Aldehyd og lattergas emissionen er blevet målt på motoren på Viking anlægget. Aldehyd emissionen var 19 gange mindre for motordrift på forgasningsgas end for drift på naturgas, mens emissionen af lattergas var 2.4 gange lavere.

Analyse af forbrændingsprocessen ved brug af en 2-zone heat release model viste et konstant og lavt niveau af cykliske variationer for et bredt spekter af λ-værdier. Dette sammenholdt med fraværet af ekstreme forbrændings-cyklusser karakteriserer forgasningsgas som et godt lean burn brændstof og indikerer at forgasningsgas kan anvendes i motorer med højt kompressionsforhold.

I forbindelse med de 3200 timers motordrift på Viking anlægget er der løbende lavet observationer af korrosion, slid og belægningsdannelsen i motoren. Det har ikke været muligt at observere et øget slid der kunne tilskrives forgasningsgassen. Med hensyn til belægningsdannelsen er der observeret en begrænset tendens til dannelse af belægninger. Ved hyppige undersøgelser af motorens topstykker og stempeltoppe er der kun observeret en tynd grå pulveragtig belægning i forbrændingskammeret. Sideløbende er der lavet analyser af smøreolien fra motoren på Viking anlægget. Resultatet af analyserne har vist, at der ikke sker nogen accelereret nedbrydning af olien ved motordrift på forgasningsgas, kun en mindre ophobning af klor i smøreolien er set efter 200-300 timers motordrift. Det vurderes, at en levetid for smøreolien minimum vil være 600-800 timer.

ENGLISH SUMMARY

The aim of this project has been the characterization of biomass producer gas as a fuel for stationary gas engines in heat and power production.

More than 3200 hours of gas engine operation, with producer gas as fuel, has been conducted at the biomass gasification combined heat and power (CHP) demonstration and research plant, named "Viking" at the Technical University of Denmark. The plant and engine have been operated continuously and unmanned.

Producer gas properties and contaminations have been investigated. No detectable tar content was observed in the gas that goes to the engine; this was confirmed by three different measuring methods. Likewise, no particles were detected in the gas. Considerable amounts of NH_3 were measured in the produced gas.

An analysis of engine operation at varying load has been carried out. Standard emissions, load and efficiency have been measured at varying operating conditions ranging from 50% to 90% load. Biomass producer gas is an excellent lean burn engine fuel: Operation of a natural aspirated engine has been achieved for $1.2<\lambda<2.8$ without significant reduction of engine efficiency.

Relatively high emission of unburned CO was seen at all operating conditions when compared to the current European regulations for CO emissions. The high CO emission from producer gas engine operation is primarily 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. NO_x emissions are in general not a problem for lean burn producer gas operation, except for producer gas with very high concentrations of NH_3.

Measurements of the emission of polycyclic aromatic hydrocarbons (PAH) showed that there were no detectable PAH in exhaust gas from the engine when it is operated on producer gas. The emissions of aldehydes and

laughter gas were measured to be significantly lower for producer gas operation than for natural gas.

Analysis of the combustion process for producer gas operation by applying a heat release model showed a constant low level of cyclic variations for a wide range of λ-values. The absence of extreme combustion cycles characterizes producer gas as a good lean burn fuel and indicates that producer gas may be applied in engines with high compression ratio.

The engine heads have been removed several times in order to inspect the internal parts for formation of deposits, wear and corrosion, and no significant built up has been seen. Frequent oil analysis has been conducted and no significant degeneration has been seen.

LIST OF THE APPENDICES:

Appendix I : *Experiments with Wood Gas Engines.* Jesper Ahrenfeldt, Torben Kvist Jensen, Ulrik Henriksen and Jesper Schramm. SAE 2001-01-3681, Copyright © 2001 Society of Automotive Engineers, Inc.

Appendix II: *Combustion Chamber Deposits and PAH Formation in SI Engines Fuelled by Producer Gas from Biomass Gasification.* Jesper Ahrenfeldt, Ulrik Henriksen, Jesper Schramm and Torben K. Jensen, Helge Egsgaard. JSAE-20030328 SAE 2003-01-1770, copyright © 2003 Society of Automotive Engineers of Japan, Inc.

Appendix III: *Investigation of Continuous Gas Engine CHP Operation on Biomass Producer Gas.* Jesper Ahrenfeldt, Torben K. Jensen, Ulrik Henriksen and Jesper Schramm. SAE 2005-01-3778, SAE 2005 Transactions Journal of Fuels and Lubricants, vol: 114-4, pp. 1464-1476 (2006). SAE International ISSN: 0-7680-1690-8.

Appendix IV: *Validation of a Continuous Combined Heat and Power (CHP) Operation of a Two-Stage Biomass Gasifier.* Jesper Ahrenfeldt, Ulrik Henriksen, Torben K. Jensen, Benny Gøbel, Lars Wiese, Alphons Kather, Helge Egsgaard. Energy & Fuels, paper id. ef0503616, 2006.

Appendix V: *CO Emissions from Gas Engines Operating on Biomass Producer Gas.* Jesper Ahrenfeldt, Torben Kvist Jensen, Ulrik Henriksen, Jesper Schramm and Benny Gøbel. Paper V2A64 in proceedings of *2nd World Conference and Technology Exhibition on Biomass for Energy and Industry*; Rome, Italy, 2004.

Appendix VI: *CO and PAH Emissions from Engines Operating on Biomass Producer Gas.* Jesper Ahrenfeldt. Knoef, H. A. M., Ed. Chapter 15, p. 284-299 in Handbook, Biomass Gasification; BTG, Biomass Technology Group: Enschede, The Netherlands, 2005, ISBN 90-810068-1-9.

1 BACKGROUND

Biomass gasification for combined heat and power production (CHP) is a promising technology which, especially in small-scale plants with an electric power output less than 10 MW, provides an attractive alternative to biomass combustion. The combination of biomass gasification and a gas engine for CHP is a logical choice in the small-scale range and with a biomass to power efficiency potential of 35-40%, which is high compared to conventional technology, these plants will be very competitive. The emerging technology of gasification makes it possible to build decentralised biomass CHP plants in a scale that has not been efficient before.

The prospect of decentralised CHP utilisation of biomass with high efficiency is appealing in a country like Denmark where district heating is widespread. It is not only applicable for the construction of new plants, but there is also huge potential for converting existing heating plants fuelled by biomass and gas engine CHP plants fuelled by natural gas. Figure 1.1 shows a map of all heating and power plants in Denmark in 2004. As can be seen there is a substantial number of biomass fired heating plants and decentralised CHP plants fuelled by natural gas. Almost all of the decentralised CHP plants fuelled by natural gas are gas engine based. Data from 2003 shows that more than 11 PJ of biomass was utilised in heating plants, and 47 PJ of natural gas was utilised in decentralised CHP plants [1].

The high power efficiency of small scale biomass gasification CHP based on gas engines provides an opportunity for converting biomass fired heating plants into efficient CHP plants that has not previously been present. An advantage of such a conversion is that infrastructure and buildings already are at hand. Natural gas fuelled gas engine CHP plants can either be converted into pure biomass based plants or dual fuel plants, operating on either producer gas or natural gas or mixtures of both. The main advantage of a conversion of such plants is that the gas engine is already at hand and thus a major part of the investment.

Since biomass producer gas is a very different fuel than hydrocarbon based gaseous fuels, such as natural gas and biogas, it has been desirable to demonstrate long term stationary gas engine operation on producer gas. The aim of this project has been to test long term gas engine CHP operation on biomass producer gas and to obtain knowledge about the utilisation of producer gas as a fuel for stationary gas engines in heat and power production. This has been done by investigating and analysing engine-operating characteristics such as emissions, performance, efficiency and other operating variables. The project has been financed by the Danish Energy Agency and it is part of a series of projects aiming at developing and demonstrating two-stage fixed bed biomass gasification for combined heat and power production [2].

As an objective of this project and two parallel running projects the Viking gasification plant at the Technical University of Denmark has been built to demonstrate continuous combined heat and power operation of a two-stage gasifier fueled by wood chips (see section 2). The plant has been operated for more than 3600 hr (3200 hr with engine operation) until august 2006. The operation of the Viking plant has been the main subject of investigation, but also data from two other CHP plants have been analysed. In parallel lab scale engine experiments have been conducted on synthetic producer gas.
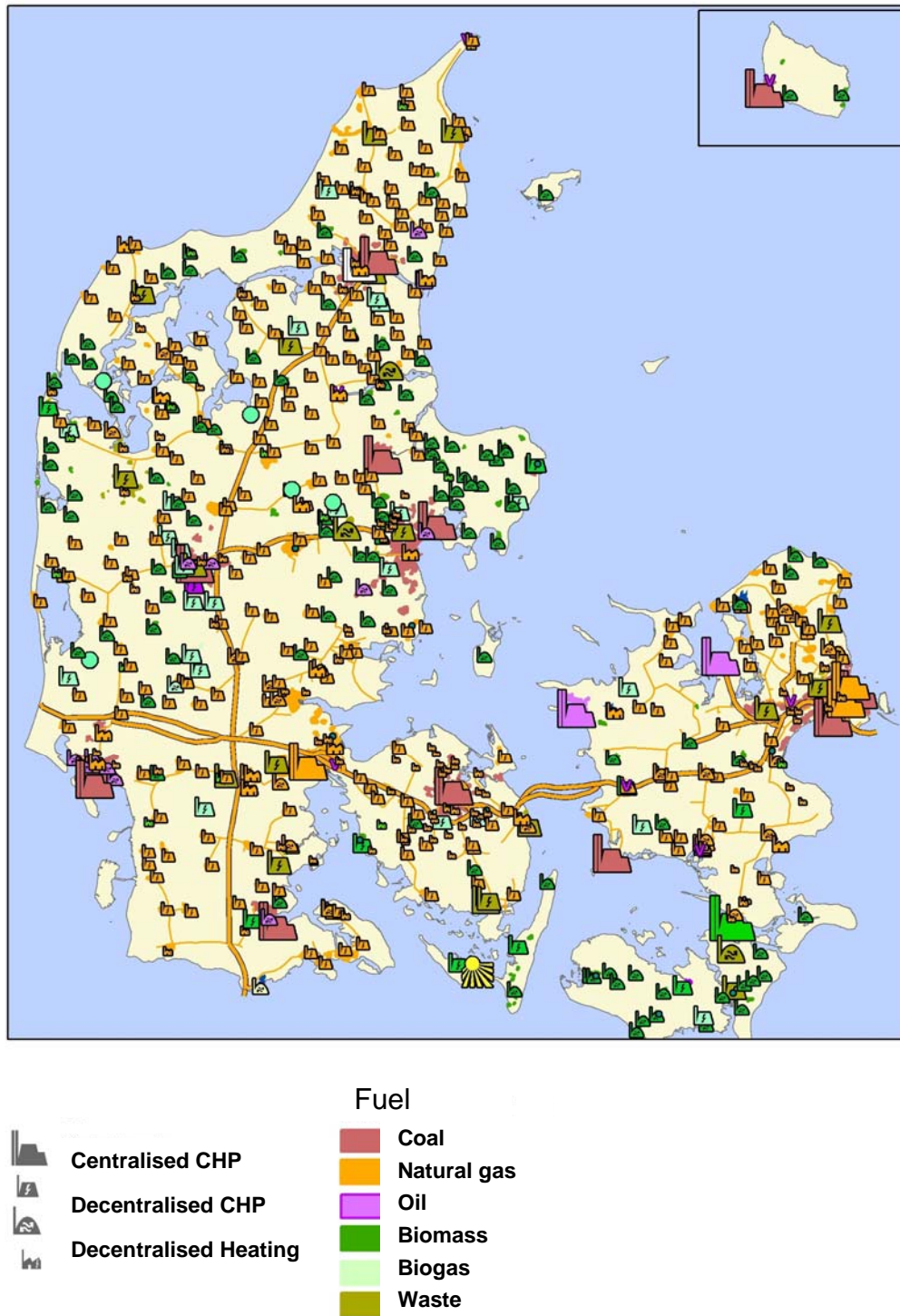
Fuel

- Coal
- Natural gas
- Oil
- Biomass
- Biogas
- Waste

Centralised CHP

Decentralised CHP

Decentralised Heating

Figure 1.1 Map of energy producing plants in Denmark [1].

2 THE VIKING GASIFICATION TEST PLANT

Since the beginning of the 1990s the reduction of CO_2 emissions has become one of the main focus areas of research and development in the power plant industry. One way to achieve this goal is to increase the energetic use of biomass which, compared to other renewable energy sources, offers the advantage of no temporal dependency on wind or sunshine. In the last 15 years a large number of plants burning biomass in order to operate a steam turbine were commissioned in Europe. Most of these plants have an output of less than 20 $MW_{electric}$ and show electrical efficiencies of less than 30%.

At small scale, units with electrical outputs of less than 10 $MW_{electric}$, gasification plants feeding the gas to an engine offer an interesting possibility for reaching higher electric efficiencies. Therefore in the past a large number of fixed bed gasifiers were developed and tested for supplying a gas engine with fuel. Unfortunately, most of these plants could not be operated over a long period of time, as it was either impossible to achieve stable operation or a too high tar concentration in the produced gas made continuous engine operation impossible.

At the Technical University of Denmark (DTU) the Biomass Gasification Group (BGG) has been working with research and development of staged gasification in fixed beds since 1989. During this period different designs have been investigated [3]. The two-stage process is characterized by having pyrolysis and gasification in separate reactors with an intermediate high temperature tar cracking zone [4]. This allows control of the process temperatures resulting in extremely low tar concentrations in the produced gas [5]. After success with process verification and design the BGG decided to build a continuous running gasifier for long term testing. As a result a biomass gasification demonstration and research plant was built. The gasification plant named "Viking" (see Picture 2.1) is a small-scale plant with a nominal thermal input of 70 kW. The plant is fuelled by wood chips, it is operating fully automated and unmanned, feeding the produced gas to a gas engine. The main target for the Viking project has been to demonstrate and test long-term CHP operation of a gasifier coupled with a gas engine. The

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plant was commissioned in the autumn of 2002 and has been operated for more than 3600 hours (3200 hours with engine operation) until August 2006. The main data of the plant are:

Table 2.1 Data from the Viking plant.

Gasification concepts	Two-stage down draft
Thermal input [kW]	70
Feedstock [-]	Wood chips
Electric output [kW]	17.5
Thermal output [kW]	39
Engine electric efficiency [%]	29
Overall electric efficiency [%]	25

Picture 2.1 The Viking demonstration and research plant.

2.1 Plant set-up

In the following section the set-up of the Viking plant and the gasification process are described.
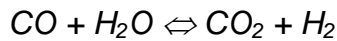
2.1.1 The feeding system

The wood chips are fed to the gasifier through a feeding system. The storage container with a conveyer in the bottom feeds the wood chips to a system of screw conveyers. The first two screw conveyers transport the wood chips to a

lock hopper system which consist of two slide valves separated by a third screw conveyer. This system secures that no gas leaks from the pyrolysis unit. After the second slide valve the wood chips are fed into a cache. From the cache a forth screw conveyer feeds the feedstock to the pyrolysis reactor. By controlling the rotational speed of this screw the feeding rate of the wood chips is controlled. The cache is purged with a small flow of nitrogen in order to avoid a back flush of gas form the pyrolysis reactor and thus tar condensation in the feeding system.

2.1.2 The pyrolysis reactor

The pyrolysis reactor consists of a screw conveyer that transports the biomass through the reactor. The pyrolysis reactor is externally heated by the exhaust gas from the gas engine. In the first part of the pyrolysis reactor the biomass is dried, and in the second part the pyrolysis takes place. Pyrolysis demands higher temperatures than drying, and to satisfy this, the exhaust gas from the engine is split into two streams (see Figure 2.1). One stream is heated further by heat exchanging with the hot producer gas and the other is led directly to the pyrolysis unit where it joins the other stream. During the pyrolysis process, volatiles are released from the biomass due to heating. The solid fraction of the pyrolysis is char.

Figure 2.1 Process flow sheet of the Viking gasifier [6].

2.1.3 The gasification reactor

The product of the pyrolysis process, char and gas, are lead to the gasification reactor. Prior to the gasification process the pyrolysis gas is partly oxidised in order to produce the heat necessary for the endothermic char gasification (see Figure 2.1). Temperatures of 1100-1300°C are reached in this oxidation zone. Due to the high temperature and the partial oxidation of the volatile pyrolysis products the tar content in the volatiles are reduced by about a factor of 100 [7].

Char gasification in the char bed is controlled by a complex set of reactions which can be described by Langmuir-Hishelwood kinetics [8]. The reacting gasification agents in the process are H_2O and CO_2 [9]. The temperature in the bed ranges from 1100 to 800 ^{o}C. Throughout the bed the composition of the gas phase will be in equilibrium for H2O, H2, CO2 and CO [10, 11, 12]. This equilibrium can be described by a single, temperature dependent reaction, the so-called water-gas shift reaction [13].

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$$CO + H_2O \Leftrightarrow CO_2 + H_2 \qquad \textbf{Reaction 1}$$

When the producer gas leaves the gasifier it has a temperature of about 750 ^{o}C. At this temperature the water-gas shift reactions are so slow that the gas composition in practise is frozen [14].

When the partially oxidised pyrolysis products pass through the char bed in the char gasification reactor, the tar content is further reduced by nearly another factor of 100 [7]. This results in extremely low tar content in the produced gas.

The gasification reactor is built with a metal shell. In the top part of the reactor, where the partial oxidation occurs, the temperatures are at the highest (up to about 1300 °C) and only gas is present. An alkali resistant refractory lining is used as reactor wall in this part of the reactor.

In the char bed, stainless steel is in direct contact with the char. This design provides a gastight reactor wall, keeping the gas from bypassing the char bed, as this would result in an increased amount of tar in the produced gas [5].

Geometrically the reactor is constructed as concentric cylinders and cones. At the bottom the cylinder meets a square grate. The grate is a moving grate, allowing ash and char to pass through in order to decrease the pressure drop over the char bed. Movement of the grate is triggered when the pressure drop across the char bed in the gasification reactor exceeds a certain threshold (e.g. 300 mm WG). Two sets of screw conveyers remove the ash.

2.1.4 The gas conditioning system

When the producer gas leaves the gasification reactor the temperature of the gas is about 750 °C. In order to cool down the gas it is passed through a system of heat exchangers (see Figure 2.1). In the first heat exchanger the gas heats up a part stream of the exhaust gas, and in the second the gas is heatexchanged to pre-heat the air for the gasifier. The gas is then cooled down to just above the water dew point (about 90 °C) in a gas/water cooler and cleaned in a bag house filter. Following the bag house filter a paper cartridge filter acts as a security filter. After this the gas is cooled further down to about 50 °C, and condensate is removed. To ensure that droplets produced

during the condensation are removed, the gas is then passed through another paper cartridge filter (similar to the security filter) which acts as demister. A roots blower drives the gas flow [15].

The bag house filter consists of ordinary polyethylene bags, which are back-flushed by nitrogen. When the pressure drop in the filter exceeds 75 mm WG the back-flush is initiated, reducing the pressure drop to about 25 mm WG.

To ensure a stable gas composition for the engine the gas is led through a mixing tank. In the tank the gas is cooled further, and condensate is removed. Leaving the mixing tank the gas has a temperature of 10-30 ^{o}C depending on the ambient temperature.

The main constituents of the produced gas are CO, H_2, CO_2, CH_4, N_2 and H_2O. The gas is a low calorific gas, meaning that the energy density is low. On dry basis the lower heating value is 5.5-6.5 MJ/Nm^3. Compared to natural gas with a lower heating value of 39 MJ/Nm^3, this is very low. On the other hand the producer gas has a stoichiometric air to fuel ratio of about 1.2 Nm$^3_{air}$/ Nm$^3_{fuel}$ compared to 10.6 for natural gas. Because of this relationship between the heating value and the stoichiometric air to fuel ratio the amount of energy in the fuel and air mixture supplied to the engine is only 10-12% lower for this producer gas than for natural gas.

2.2 Engine set-up

The produced gas is fed to a naturally aspirated 3-cylinder 3.1 litre DEUTZ spark ignition gas engine operating at variable load. The engine is connected to a producer gas and natural gas line. Natural gas is used during the start up. During the start up of the plant the engine is operated on natural gas in order to produce the necessary heat for the drying and pyrolysis reactor. When the gasifier is running stable, the gas cleaning system is activated. For a short period of time the cleaned gas is flared. This is done in order to secure a stabilized gas cleaning. When the plant is producing good quality gas the engine is switched to producer gas operation.

The produced electricity is supplied to the electricity grid. The produced heat from cooling of the producer gas and the exhaust gas as well as from the cooling of the engine is supplied to a heating system in order to simulate

district-heating operation. The forward temperature of water is 65-70 °C while the return temperature from the central heating system is kept constant at 35 °C.

The engine is operated with full open throttle at all loads during operation on producer gas. A roots blower supplies the gas to the engine and the combustion air is naturally aspirated by the engine. Gas and air are mixed by a mixing device located in the supply pipe prior to the intake manifold. The local gas grid supplies the natural gas. Figure 2.2 shows a diagram of the engine set-up.
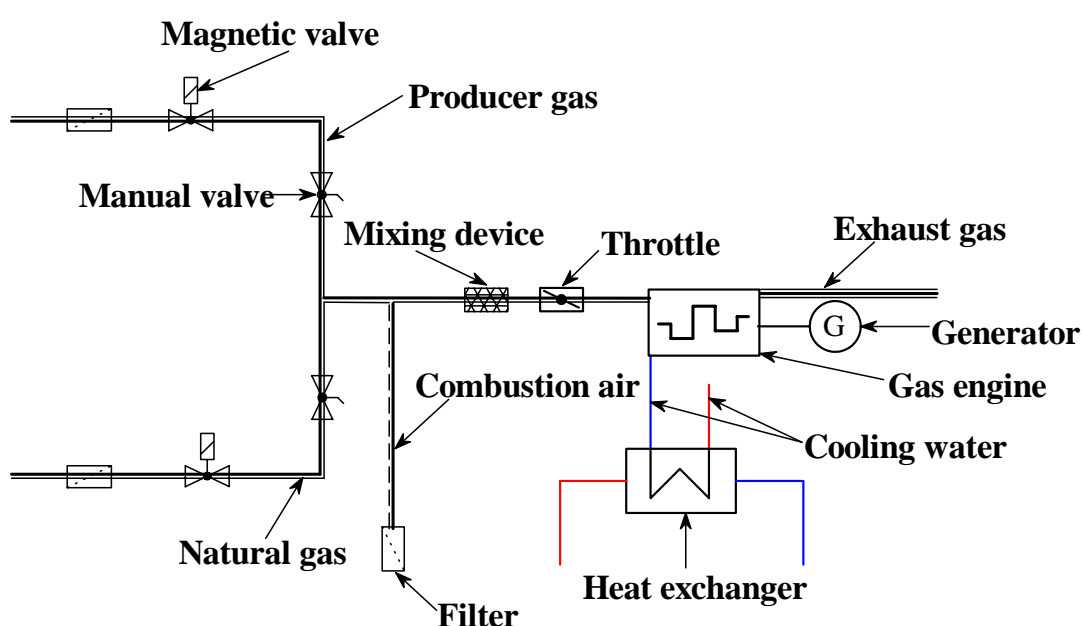

Figure 2.2 Diagram of the engine set-up

2.3 Plant control

The gasifier control and security systems are automatically handled by a PLC (programmable logic controller) and the plant can be operated unattended. Two different overall control approaches for the plant can be applied:

1. Produce a constant gas flow to the engine. In order to obtain this, the roots blower, which is a volumetric machine, is operated at constant speed. The addition of air to the gasifier is automatically adjusted to give atmospheric pressure at the biomass feedstock inlet in the pyrolysis unit.

2. Keep a constant excess of air (O_2%) in the exhaust gas from the engine. The O_2% is measured by an oxygen sensor in the exhaust pipe, and the flow rate of gas from the gasifier is varied by the gas blower in order to keep a constant O_2%. The flow varies because the composition of the producer gas from the gasifier varies. The addition of air to the gasifier is automatically adjusted to give atmospheric pressure at the biomass feedstock inlet in the pyrolysis unit.

The first control strategy gives a more stable operation of the gasifier due to the constant gas flow from the gasification reactor. On the other hand the variations in gas composition will result in variations in engine performance. The second strategy gives a more stable engine performance but the varying gas flow can give a less stable char gasification.

3 BIOMASS GASIFICATION CHP PLANTS

The following gives a short description of two other operating full scale biomass gasification CHP plants from which data has been analysed. These plants have been chosen for analysis because; a) they were, at the time, the only gas engine based CHP plants operating continuously, b) data was available, c) they represent, including the Viking process, tree different biomass gasification processes and thus they exemplify the diversity of biomass producer gas.

3.1 The Harboøre Plant

The CHP plant in Harboøre is an air-blown updraft gasifier (5200 kW$_{th}$) that converts wood chips into producer gas with a lower heating value of approximately 6 MJ/Nm^3 (dry basis, tar-free) [16]. The plant is designed for unattended operation. After the gas conditioning, the product gas is used as fuel in two gas engines with generators producing electricity for the grid. The main data of the plant is:

Table 3.1 Data from the Harboøre plant.

Gasification concepts	Up draft
Thermal input [MW]	5.2
Feedstock [-]	Wood chips
Electric output (2 engines) [kW]	1400
Thermal output [kW]	3400
Operating λ [-]	2.2-2.4
Engine electric efficiency [%]	40
Overall electric efficiency [%]	28

The plant is located at the municipality of Harboøre, on the northwest coast of Jutland, Denmark). The plant was designed by Babcock & Wilcox Vølund. **Figure 3.1** below shows a process flow sheet of the Harbøre plant.
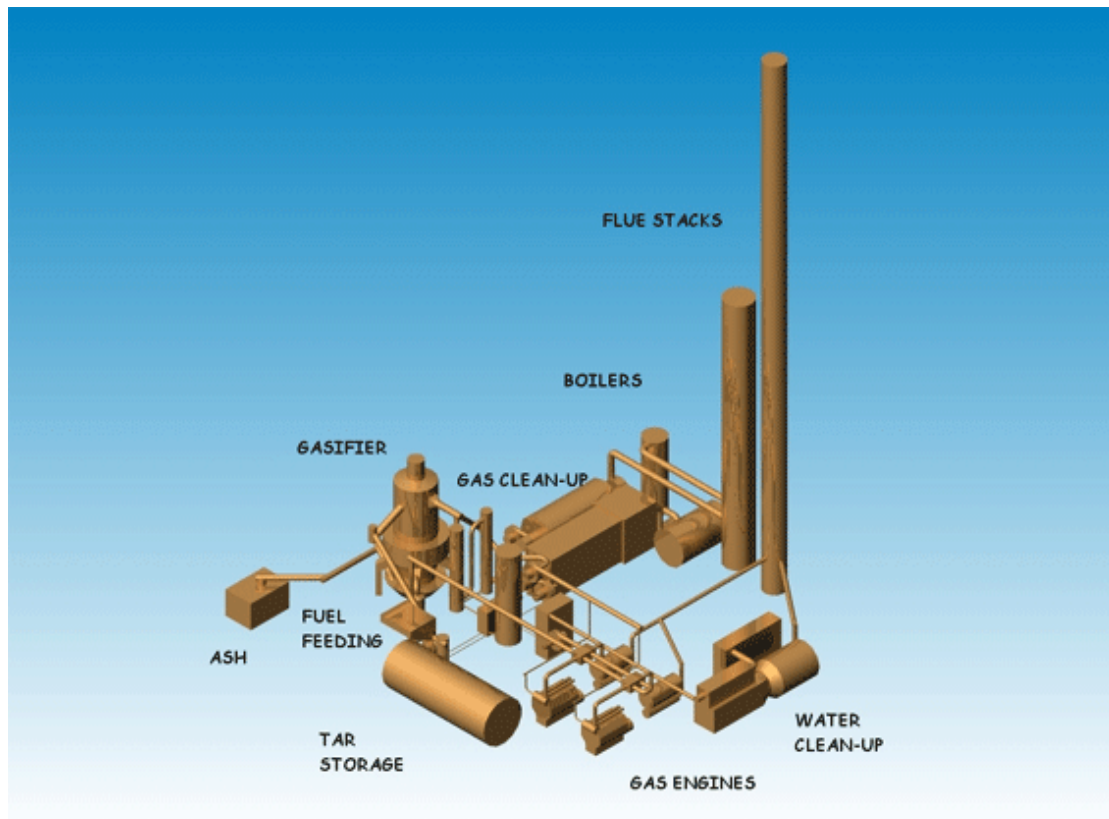
Figure 3.1 A process flow sheet for the CHP plant in Harboøre [16].

The raw product gas exits the gasifier at a temperature of about 75 °C. It contains about 80 g/Nm^3 of various tars and acids and also a small amount of particles. At the first step of the gas conditioning system, the raw product gas is cooled down to a temperature of about 45 °C supplying heat for the local district heat grid. The cooling results in condensation of a considerable amount of water and tar. In the following step, the majority of the remaining tar components in the product gas are removed in a wet electrostatic precipitator. After this, the amounts of tars and dust are each below 25 mg/Nm^3. The product gas is fed to the engines by a booster-fan, which ensures a suitable pressure of the product gas.

3.2 The Güssing Plant

The CHP plant at Güssing in Austria is a FICFB (Fast Internal Circulating Fluidised Bed) steam gasifier (8 MW$_{th}$) that converts wood chips to a product gas with a heating value of approximately 12 MJ/Nm^3 (dry basis). After the gas conditioning at the plant (a two-stage gas cleaning system), the product gas is used as fuel in a gas engine with a generator producing electricity for

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the grid. If the engine is not in operation, the product gas can be burned in a boiler producing heat. The main data of the plant is:

Table 3.2 Data from the Güssing plant.

Gasification concepts	Fast internally circulating fluidised bed (FICFB)
Thermal input [MW]	8
Feedstock [-]	Wood chips
Electric output [MW]	1.5
Operating λ [-]	2.2-2.4
Engine electric efficiency [%]	39
Overall electric efficiency [%]	25

The plant was built between September 2000 and October 2001. **Figure 3.2** below shows a process flow sheet of the CHP plant in Güssing.
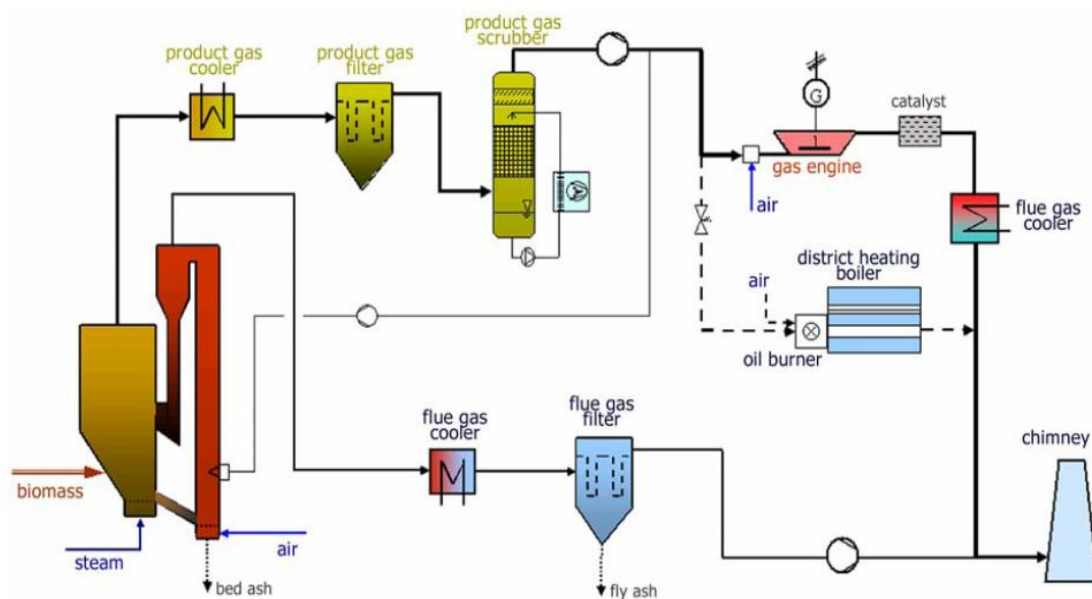

Figure 3.2 A process flow sheet for the CHP-Plant at Güssing [17]

The FICFB gasifier consists of two zones; a gasification zone and a combustion zone. The combustion zone provides heat through the bed material to the gasification zone. Steam is used as gasification agent in the gasification zone. This should in itself lead to a lower tar content compared to air blown gasifiers [17]. Olivine sand is used as bed material. The amount of tar in the raw product gas from the gasifier is about 1500 – 4500 mg/Nm^3 (dry

gas). Leaving the gasifier, the product gas is cooled down to a temperature of about 160-180 °C. The product gas is passed through a fabric filter, removing the particles and some of the tar. The fabric filter is coated with material that is released when the filter is back-flushed. The released material consists of particles and some amounts of tar and is led back to the combustion zone of the gasifier. After this step, the product gas is led to a scrubber using 'oil' (RME) as scrubber liquid. Spent scrubber liquid saturated with tar and condensate is vaporized and led to the gasifier in the combustion zone. The amount of tar exiting the fabric filter is about 750 mg/Nm^3 dry gas. Leaving the scrubber, the clean product gas has a very low tar content of about 10-40 mg/Nm^3 dry gas. The exhaust gas of the engine is catalytic oxidised to reduce the CO emissions.

4 PRODUCER GAS AS ENGINE FUEL

The following sections give a description of biomass producer gas as an engine fuel. The main focus will be on the gas from the Viking plant but in order to illustrate the diversity of producer gas data from the Harboøre and Güssing plants is also included.

The difference in gas composition from gasifiers are due several factors; gasification process (updraft, downdraft, fluid bed, see section 2 and 3), gasification agent (air, CO_2, steam, O_2) and the biomass feedstock [14].

4.1 Gas compositions

The gas produced from biomass gasification is entitled producer gas. The producer gas is, beside small amounts of impurities, primarily a mixture of CO, H_2, CO_2, CH_4, N_2 and H_2O. Table 4.1 shows an example of the average gas composition from the three plants. It is notable how big a variation there is in the gas composition from three plants. One of the most predominant differences is that the Güssing gas only contains 3% of N_2 compared to 41% and 34% for the Harboøre and Viking gas respectively. This difference is mainly due to the fact that the Güssing plant uses steam as gasification agent whereas the Harboøre and Viking plants primarily are using air as gasification agent. The low content of N_2 in the Güssing gas also affects the magnitude of the other components.

The Viking gas differs significant from the other two gasses in content of hydrocarbons, this is due difference in gasification process. The Harboøre gasifier is a down draft gasifier which is operated at low process temperatures, resulting in a gas with high CH_4 and CO content and low H_2 content (see section 3.1). The Güssing gasifier is a fluid bed gasifier (see section 3.2) operating at medium temperatures with steam as gasification agent which results in a gas with a high content of CH_4/C_2H_6 and H_2 and a relative low content of CO. As explained in section 2, the Viking gasifier is a two stage gasifier in which the pyrolysis gas is partially oxidised at temperatures above 1000 $^\circ$C, resulting in a low CH_4 content and a high CO

content. The high moisture content of the feedstock and high gasification temperatures result in a high H_2 content.

Table 4.1 Examples of the average dry gas composition of producer gas from different plants.

Component	Harboøre	Güssing	Viking
CO [Vol. %]	23	31	20
CO2 [Vol. %]	12	17	15
H2 [Vol. %]	19	37	30
CH4 [Vol. %]	5	9	1
C2H6 [Vol. %]	-	2	-
N2 [Vol. %]	41	3	34

Since gasification of biomass is a dynamic process, the gas composition from a gasifier will not be stable. Variations in e.g. moisture content of the feedstock will influence the gas composition instantaneously. Figure 4.1 and Figure 4.2 show measurements of the gas composition over time from the Viking and the Harboøre plant respectively. It is seen that over a period of about 24 hours the gas composition is fluctuating significantly. This will of course have an influence on engine operation, performance and emissions as will be shown in the following section. A description of the methods applied for the gas composition measurements from the Viking gasifier is given in **Appendix III**. The gas composition measurements from the Harboøre gasifier were conducted in a similar manner.
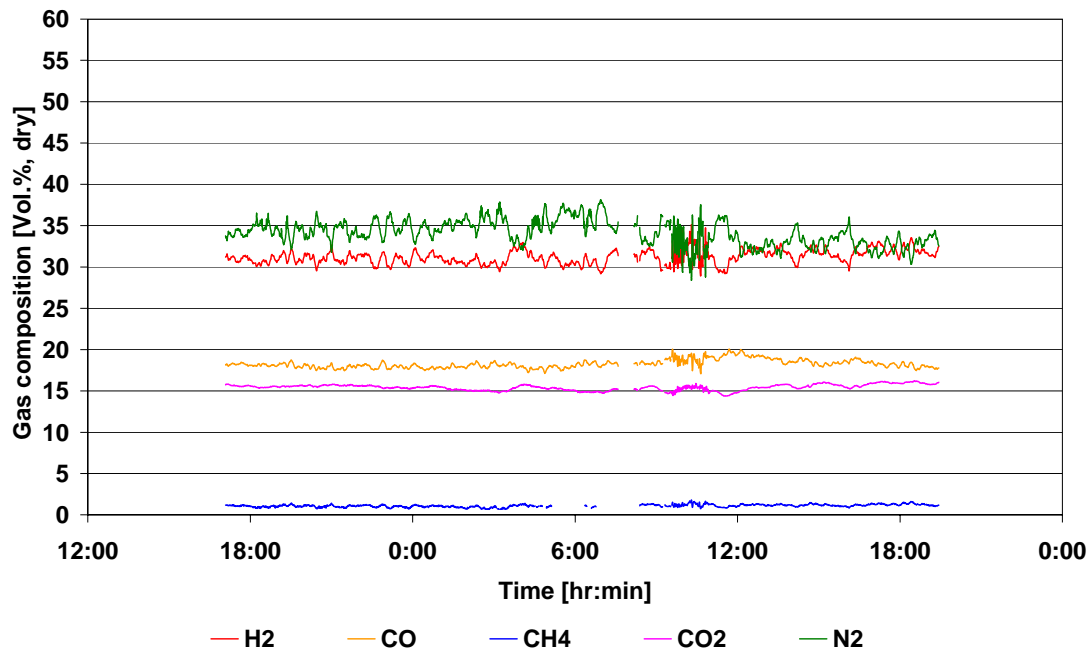
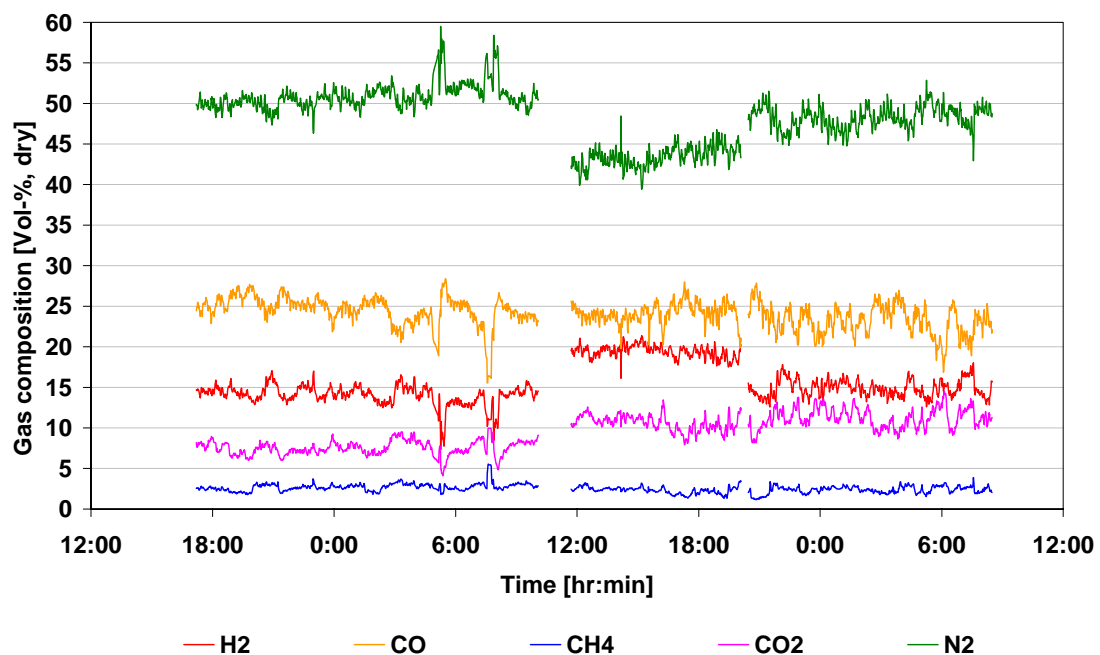**Figure 4.1 Gas composition from the Viking gasifier.**

Figure 4.2 Gas composition from the Harboøre gasifier.

4.2 Heating values and stoichiometric air-fuel ratio

In general producer gas is a low-calorific gas meaning that the energy density is very low compared to natural gas (NG). Likewise the stoichiometric air/fuel ratio of producer gas is very low, cf. Table 4.2. As seen from the table the values for the Harboøre and the Viking gas are quite similar, whereas the Güssing gas is significantly different. The difference in lower heating value

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(LHV) is mainly due to the low content of N_2, but also the relatively high content of hydrocarbons, cf. Table 4.1. A high stoichiometric air-fuel ratio for the Güssing gas, in comparison with the Harboøre and the Viking gas, is also due to hydrocarbon contents.

Table 4.2 Examples of the average lover heating value (LHV), the stoichiometric air-fuel ratio of the producer gas from the different plants and LHV of a stoichiometric air and fuel mixture.

	Harboøre	Güssing	Viking	NG
LHV [MJ/Nm$^3_{dry}$]	5.5	12.1	6	39
A/F$_{stoichiometric}$ [Nm^3/Nm^3]	1.2	2.7	1.3	10.6
LHV [MJ/Nm$^3_{stoichiometric mix.}$]	2.5	3.2	2.6	3.4

Even though producer gas has a low LHV, the low stoichiometric air-fuel ratio still makes it a good engine fuel. The Viking gas, as an example, has a LHV of 6 MJ/Nm^3. In comparison to natural gas with a LHV of 39 MJ/Nm^3, this is very low. On the other hand, the producer gas has a stoichiometric air/fuel ratio of about 1.3 Nm$^3_{air}$/Nm$^3_{fuel}$ compared to 10.6 for natural gas. Because of this relationship between the heating value and the stoichiometric air/fuel ratio, the amount of energy in a stoichiometric air-fuel mixture supplied to the engine is only about 20% lower for this producer gas than for natural gas. The reduction is about the same for the Harboøre gas while for the Güssing gas the reduction is only 6% compared to natural gas.

Fluctuations in the gas composition as was seen for the Viking and Harboøre gas will of course affect the LHV and the stoichiometric air-fuel ratio. Figure 4.3 and Figure 4.4 show the LHV and the stoichiometric air-fuel ratio for the Viking and the Harboøre gas corresponding to the gas composition as seen in Figure 4.1 and Figure 4.2. Relatively large fluctuations are seen for both gasifiers and cf. Table 4.3 and Table 4.4 there is a significant difference between the minimum and maximum values. However as depicted in Figure 4.3 and Figure 4.4, this variation is to some extent balanced out by a corresponding variation in the stoichiometric air-fuel ratio. For the Viking gas there is a 22% difference between maximum and minimum for LHV, while there only is 9% difference for LHV for a stoichiometric air-fuel mixture. For the Harboøre gas the same numbers are 34% and 17%. This effect results in

stable and controllable engine operation despite relatively large variations in gas composition.
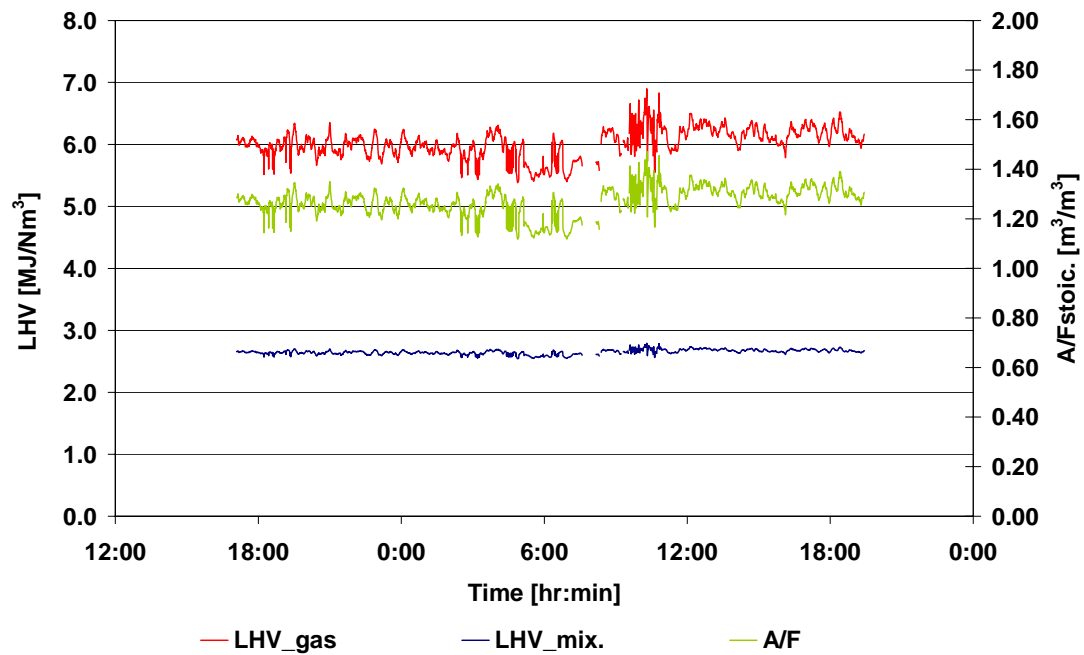

Figure 4.3 The LHV, stoichiometric air-fuel ratio and the LHV of a stoichiometric air-fuel mixture for the Viking gas.
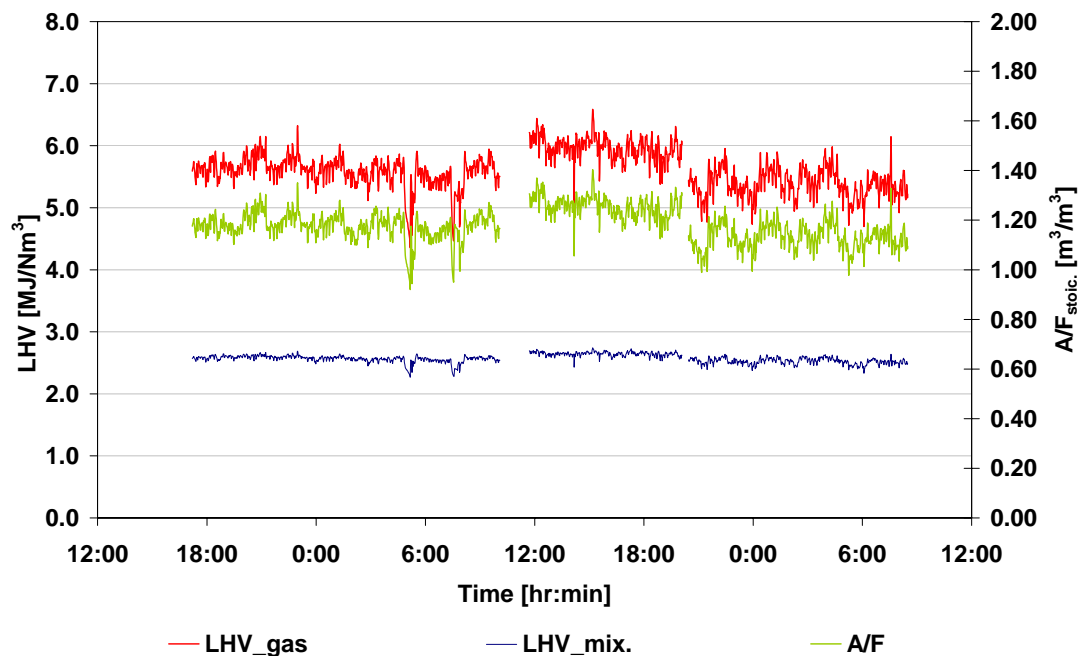

Figure 4.4 The LHV, stoichiometric air-fuel ratio and the LHV of a stoichiometric air-fuel mixture for the Harboøre gas.

Table 4.3 Statistics for the LHV, stoichiometric air-fuel ratio and the LHV of a stoichiometric air-fuel mixture for the Viking gas.

Viking	LHV [MJ/Nm$^3_{dry}$]	A/F$_{stoichiometric}$ [Nm^3/Nm^3]	LHV [MJ/Nm$^3_{stoichiometric\ mix}$]
Max.	6.9	1.5	2.8
Min.	5.4	1.1	2.5
Average	6	1.3	2.7
Standard dev.	0.2	0.06	-

Table 4.4 Statistics for the LHV, stoichiometric air-fuel ratio and the LHV of a stoichiometric air-fuel mixture for the Harboøre gas.

Harboøre	LHV [MJ/Nm$^3_{dry}$]	A/F$_{stoichiometric}$ [Nm^3/Nm^3]	LHV [MJ/Nm$^3_{stoichiometric\ mix}$]
Max.	6.6	1.4	2.7
Min.	4.4	0.9	2.3
Average	5.6	1.2	2.6
Standard dev.	0.3	0.07	-

Stationary gas engines for CHP are typically operated lean burn, hence the combustion takes place under conditions where an excess of air is present. Natural gas fuelled engines are operated at an excess of air (λ) of 2-2.5. For lean combustion of natural gas the use of a turbocharger is necessary in order to assure that misfiring and irregularities will not appear and in order to produce an acceptable mean effective pressure (MEP).

The main advantages of operating the engine lean are that it is possible to achieve higher engine efficiency and that NO$_x$ emissions are reduced due to the lower combustion temperatures. By turbocharging the engine a high power out put can be archived.
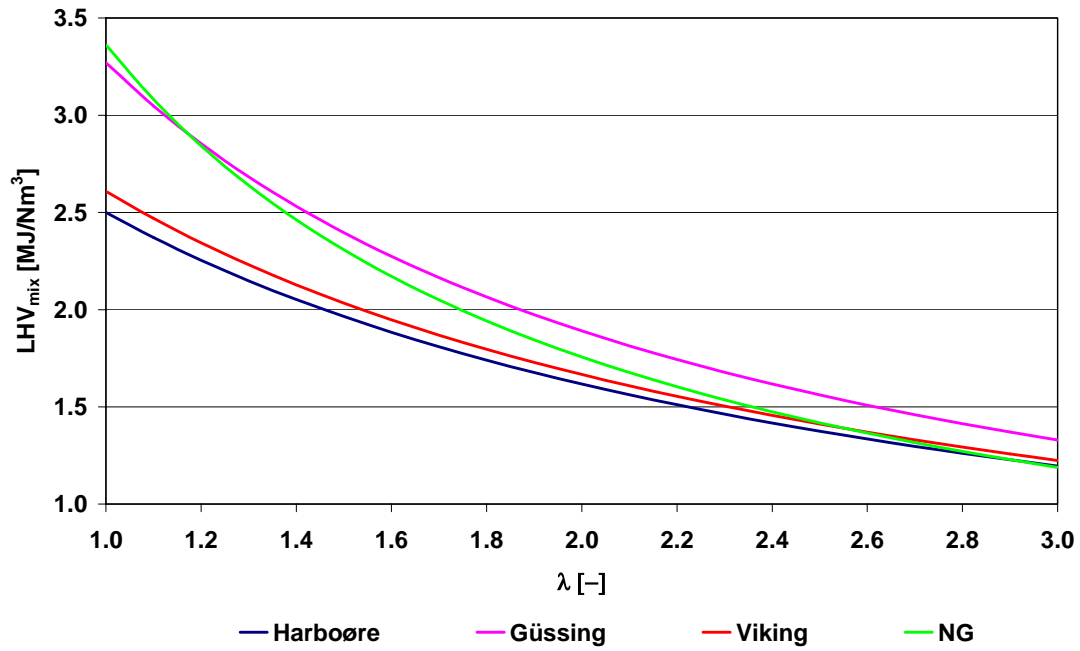
Figure 4.5 The LHV of an air-fuel mixture depicted as a function of the excess of air (λ).

One of the main conclusions of this study is that biomass producer gas is an excellent lean burn fuel. An indication of this is shown in Figure 4.5 where the LHV of air-fuel mixtures is depicted as a function of the excess of air (λ) for the different producer gases and for natural gas. Whereas there is a difference of 20% in favor of natural gas at λ=1.0 compared to the Viking gas, at λ=2.5 the difference is 0%. For the Güssing gas it looks even better, already at λ=1.2 the LHV$_{mix}$ is equal to natural gas and at λ=2.5 it is 9% higher. It is the low stoichiometric air-fuel ratio of the producer gas that results in this property.

4.3 Gas quality

The product gas exiting a biomass gasifier normally contains some amount of particles, alkali compounds, tars and nitrogen containing components. Depending on the design of the gasifier and the type of biomass used as fuel, there can be more or less of the components mentioned above. These contaminants are normally incompatible with trouble-free gas engine operation and therefore some gas cleaning is required.

Table 4.5 Indicative specifications of product gas for gas engines

Reference	[18]	[19]
Tar [mg/Nm^3]	< 50	< 50
Particles [mg/Nm^3]	< 5	< 50
Alkalis [mg/Nm^3]	-	< 1
Ammonia [mg/Nm^3]	-	< 50
Chloride [mg/Nm^3]	-	< 10
Sulphur (H_2S, COS) [mg/Nm^3]	-	< 100

4.3.1 Tars and particles

Tars in the producer gas have been one of the main constrictions regarding the use of producer gas as fuel for a gas engine. The quantity of tars that some gasification systems generate may ruin internal parts of a modern gas engine. Even though novel gas cleaning systems are highly efficient, it is inevitable that small quantities of tar will reach the engine.

In the gasification the tars are formed during the pyrolysis process which initiate at about 230°C, where the complex polymers in the biomass are broken down resulting in a gas consisting mainly of CO_2, H_2O, CH_4, CO, H_2, tar and char. The tar consists of various heavy organics that can condense and break down in subsequent processes [20]. Various definitions of tar exist According to the IEA Gasification Task [21], "all organics boiling at temperature above that of benzene should be considered as tar". According to the tar protocol [22], tars are hydrocarbons with a molecular weight higher than benzene (>78 kg/kmol). A more comprehensive description of tar formation can be found in [23, 24, 25]. Examples of tar concentrations from the Harboøre, Güssing and Viking plants are provided in the following.

During this study extensive measurements of the tar content in the producer gas from the Viking plant have been conducted (see **Appendix III** and **Appendix IV** for description of measurements and methods). The Viking gasifier is a low-tar gasifier (see section 2), meaning that the produced tars are decomposed in the process and only very small quantities end up in the producer gas. Table 4.6 shows an example of the result of a tar measurement. The only compound that could be detected was 0.02-0.1

mg/Nm^3 of naphthalene in the raw producer gas before gas cleaning. After gas cleaning no tars could be detected in the gas. Analysis for polynuclear aromatic hydrocarbons (PAH) showed no detection.

Table 4.6 GC/MS analysis of tar measurements from the Viking gas.

Measuring point	Raw gas	Raw gas	Raw gas	Raw gas	Clean gas	Clean gas	Clean gas	Clean gas
Phenol [mg/Nm$^3_{dry}$]	<0.01	<0.03	<0.07	<0.15	<0.03	<0.05	<0.49	<0.05
Guaiacol [mg/Nm$^3_{dry}$]	<0.02	<0.02	<0.1	<0.05	<0.03	<0.02	<0.1	<0.03
Naphthalene [mg/Nm$^3_{dry}$]	0.07	0.02	0.05	0.1	<0.01	<0.03	<0.03	<0.01
PAH$_x$ [mg/Nm$^3_{dry}$]	<0.01	<0.001	<0.02	<0.03	<0.01	<0.002	<0.06	<0.06

As can be seen from Table 4.7 the two other gasifiers are producing large amounts of tars. Even after extensive cleaning (see section 3) there are still significant amounts of tar in the producer gas. These tars can cause mild to critical problems for the engine. For example high amounts of naphthalene can result in formation of crystals in the intake system and cause blockage. Likewise tars can cause deposit formation in the turbocharger system and the intercooler [26]. High tar content can also affect engine operation parameters. The relative high tar content in the Güssing gas has the implication that the engine inlet gas temperature has to be maintained above 50 ^{o}C in order to avoid tar condensation.

The main tar components in the Harboøre gas are phenols [27]. High amounts of phenols in the gas are suspected to cause formation of combustion chamber deposits (CCD) and thus increase engine wear. During this study extensive experimental investigations were made concerning the formation of combustion chamber deposits caused by the presence of light tar compounds such as phenol and guaiacol. The work is published in **Appendix II** and a summery of the results is provided in section 8.

Table 4.7 Overall tar amounts in the raw and cleaned gas form the Harboøre and the Güssing plants

	Harboøre	Güssing
Raw gas [mg/Nm^3]	80000	1500-4500
Cleaned gas [mg/Nm^3]	25	10-40

Due to extensive filtering, particles in clean gas from the gasifiers are not a problem, cf. Table 4.8.

Table 4.8 Measurements of the particle contents of the producer gas from the different plants.

	Harboøre	Güssing	Viking
Particles [mg/Nm^3]	6	-	< 5

4.3.2 H$_2$S/COS/Cl

Measurements of the content of sulphur compounds and chlorine in the Viking gas have been conducted, but since the concentrations are very low, (due to the relative low contents of these compounds in the wood fuel, see **Appendix IV**), detection was not possible. Table 4.9 shows the results of the measurements. No data from the other plants is available.

Table 4.9 Measurements of H$_2$S, COS and Cl in the Viking gas.

	Raw gas	Clean gas
H2S [ppm]	-	< 2
COS [ppm]	-	0.93
Cl [mg/Nm^3]	6.67	n.d.

4.3.2.1 Methyl chloride

At the Harboøre plant significant amounts of methyl chloride (30 ppm) have been measured in the producer gas. The formation of methyl chloride during gasification is not yet fully understood but initial investigations indicate that formation is very dependent on the gasification process temperatures, cf. Figure 4.6.
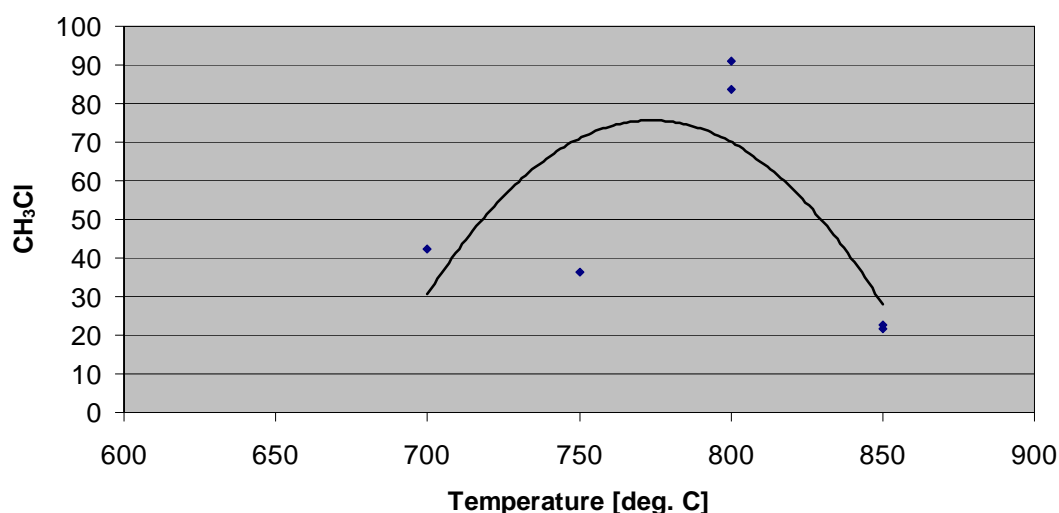
Figure 4.6 The relationship between CH₃Cl formation and temperature for wood pyrolysis, from [28].

Table 4.10 below shows measurements from three different gasifiers. As mentioned above, the Harboøre gas has a relative large content of methyl chloride, while no methyl chloride has been detected for the Viking gas. For comparison the methyl chloride content of gas from a low temperature fluid bed gasifier operating on straw is shown. As can be seen the values are significantly higher when biomass with high chlorine content, e.g. straw, is used as fuel.

Table 4.10 Measurements of methyl chloride from different gasifiers

Gasifiers	CH₃Cl
Harboøre (wood) [ppm]	30
Viking (wood) [ppm]	n.d.
Low temperature circulating fluid bed LT-CFB (straw) [ppm]	200-300

The major part of the methyl chloride will be oxidised during the combustion in an engine, and the resulting product will be HCl. The rest will be emitted as part of the fuel-slip from the combustion process (see section 6.1.1.2). Some of the HCl in the exhaust gas will react with lubricating oil film on the cylinder walls and be accumulated in the engine oil as organic Cl and cause degradation (see section 8.2). The HCl in the exhaust gas may cause corrosion problems in low temperature parts of the gas system where condensation takes place e.g. condensing coolers.

4.3.3 NH$_3$

Ammonia in the producer gas is an impurity that has a direct effect on the emissions from the gas engine. In a lean burning gas engine the ammonia in the producer gas will oxidise, and the product is primarily NO$_x$ [29]. Since regulations on NO$_x$ emissions are strict it is not beneficial to have the ammonia in producer gas contributing to the NO$_x$ emission.

Ammonia in the producer gas originates form the nitrogen that is present in the wood chips and is formed during the thermal processes in the gasifier. The ammonia formed during the gasification process will be present in the raw producer gas coming from the gasifier, along with a high content of water vapour. Depending on the moisture content of wood chips, when the gas is cooled down below the water dew point, the water present in the gas will condense. This condensate will, due to the high solubility of ammonia in water, contain a major fraction of the ammonia that was present in the raw gas. The ratio of the ammonia fraction in the gas versus the ammonia fraction in the condensate is a function of the gas temperature. It is possible to reduce or remove the ammonia content in the gas completely by washing the gas with water, as this will dissolve the ammonia in the water.

Table 4.11 Measurements of the ammonia content in the raw and clean Viking gas.

	Raw gas	Clean gas
NH$_3$ [mg/Nm$^3_{dry}$]	522-545	63.8-141

Table 4.11 shows measurements of the ammonia content in the raw gas before cleaning and condensation and in the clean gas after condensation for the Viking plant. It can be seen that there is a reduction in the ammonia content of 74%-88%. Assuming that all the ammonia in the producer gas is converted to NO in the engine, this will result in an NO emission of 41-90 mg/Nm^3@ 5% O$_2$. When assessing the NO$_x$ emission regarding regulations, NO has weight as NO$_2$. This means that the ammonia content in the gas will correspond to a NO$_x$ emission of 63-140 mg/Nm^3@ 5% O$_2$. An additional NO$_x$ emission of this proportion is not convenient and will make it harder to meet the given regulations, e.g. in Germany the regulated limit for NO$_x$ emissions is set to 500 mg/Nm^3@ 5% O$_2$ [30].

As mentioned above, the Güssing plant is operating with a high engine inlet gas temperature in order to be above the tar dew point. This results in a high content of water and thus ammonia in the gas; up to 440 mg/Nm^3 have been measured [26]. Investigations have shown that about 60% of NO$_x$ emissions from the engine at the Güssing plant originates from the ammonia.

The Harboøre gas has a very low ammonia content of about 0.01 mg/Nm^3.

5 PERFORMANCE CHARACTERISTICS

Table 5.1 below shows the nominal power out put and efficiencies for the engines at the three plants. It is particularly interesting to see that even though the two full scale engines have a much higher engine electric efficiency (from gas to electricity) the overall electric efficiencies (from biomass to electricity) are almost the same. The reason for the high overall electric efficiency of the small scale Viking plant is the high gasifier cold gas efficiency (>92%) of the two-stage biomass gasification process (see **Appendix IV**). Table 5.1 implies that a full scale two-stage gasifier plant with a high efficient turbo charged gas engine will be able to achieve overall electric efficiencies above 37%.

Table 5.1 Engine and overall electric efficiencies

	Harboøre	Güssing	Viking
Power output [kW]	750	1500	17
Engine electric efficiency (from gas to electricity, based on LHV) [%]	40	39	29
Overall electric efficiency (from biomass to electricity, based on LHV) [%]	28	25	25

In the following section the performance of the Viking engine is described. The measurements have been made in order to define the characteristics of engine operation on biomass producer gas. The corresponding emission measurements are given in section 6.1.1 below. The engine has been operated with full open throttle at all load conditions, both during operation on producer gas and natural gas. A roots blower supplies the gas to the engine, and the combustion air is naturally aspirated by the engine. Gas and air are mixed by a mixing device located in the supply pipe prior to the intake manifold (see section 2.2). Measurement procedures are described in **Appendix III** and **Appendix IV**.

5.1 Dependency on air-fuel ratio and ignition timing

To describe engine operation in terms of the air-fuel ratio the term excess of air or specific air-fuel ratio (λ) is used. The term is defined by the ratio of the actual air-fuel ratio and the stoichiometric air-fuel ratio [33].

$$\lambda = \frac{\left(A \big/ F \right)_{Actual}}{\left(A \big/ F \right)_{Stocio.}}$$

Equation 5.1

Figure 5.1 shows measurements of the power output and the shaft efficiency of the engine. It is notable that it is possible to reduce the power output by 44% with only a minor decrease in efficiency. This performance characteristic of the engine when operated on producer gas shows that the gas is an excellent lean burn fuel. Comparing producer gas operation with natural gas operation on the same engine emphasizes this advantage, cf. Figure 5.2. For natural gas operation on this engine the lean burn limit is about $\lambda \approx 1.8$ whereas for producer gas operation the limit is close to $\lambda \approx 3$. The high lean burn limit of producer gas makes it very suitable for stationary power production, cf. section 4.

Additional information about performance characteristics for producer gas operation can be found in **Appendix I**, **Appendix III** and **Appendix IV**. In **Appendix I** it is shown how the addition of producer will enhance the lean burn limit of an engine operating on natural gas (see also [31]).
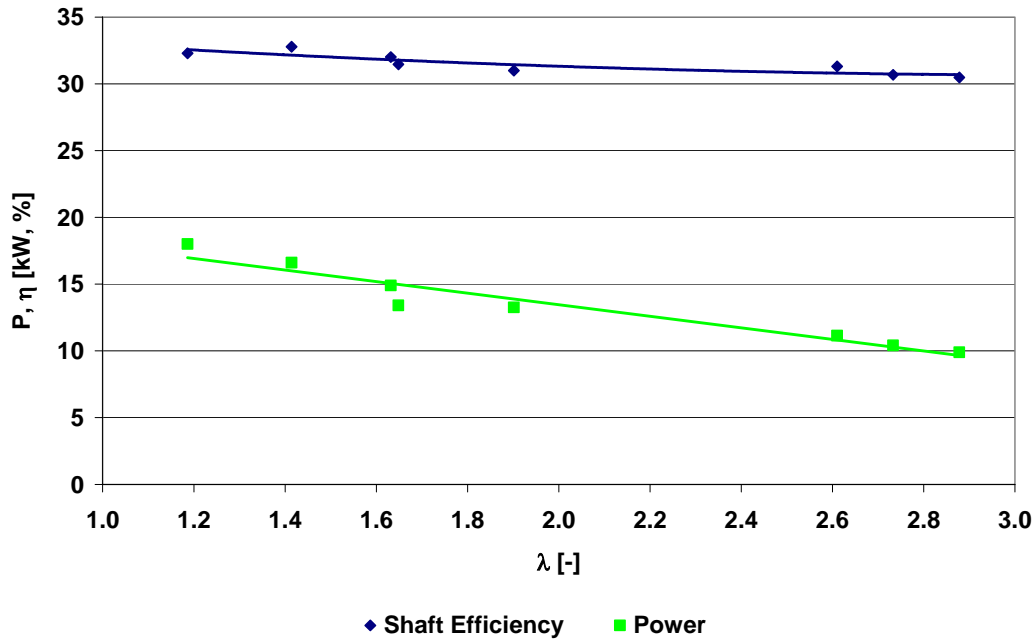
Figure 5.1 Power and shaft efficiency characteristics for the Viking engine
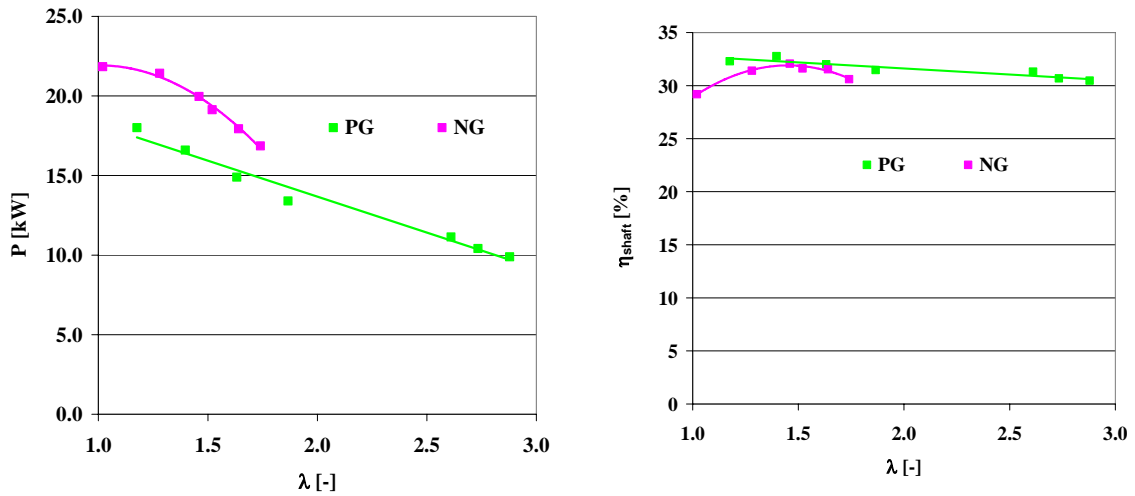

Figure 5.2 Power and shaft efficiency characteristics for producer gas and natural gas operation.

Experiments have been conducted with the aim of investigating the influence of ignition timing on the performance and emissions for producer gas operation. The results for performance are shown in Figure 5.3 and Figure 6.8 below, and the corresponding emission results are presented in section 6.1.1.1.

For four different load conditions (1.2<λ<1.9) power and efficiency have been determined with varying ignition timing. The limit to which extent the ignition

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timing could be retarded was set by the unstable engine operation e.g. misfiring and backfiring.

Table 5.2 shows the characteristics of the producer gas for each load condition. It has been essential for this experiment to have a constant gas composition and LHV in order be able to make a valid comparison between measurements. Very small variations are seen both in gas composition and LHV.

Table 5.2 The characteristics of the gas composition during the experiments with varying ignition timing.

λ	H2 [%] Average / Standard deviation / Max / Min	CO [%] Average / Standard deviation / Max / Min	HC4 [%] Average / Standard deviation / Max / Min	LHV [MJ/Nm^3] Average / Standard deviation / Max / Min
1.20	29.1/1.1/31.1/27.9	18.8/0.5/19.7/18.3	1.2/0.3/1.7/0.9	5.9/0.2/6.3/5.7
1.40	29.5/1.0/31.1/27.7	17.6/0.5/18.3/16.3	1.2/0.2/1.5/1.0	5.8/0.2/6.1/5.4
1.65	29.4/1.2/31.5/27.9	17.7/0.5/18.3/16.9	1.1/0.2/1.5/0.8	5.8/0.2/6.2/5.5
1.90	28.0/1.4/29.9/25.9	18.1/0.3/18.5/17.2	1.1/0.3/1.5/0.8	5.7/0.2/6.0/5.4

For all load conditions an increase in power and efficiency for retarded ignition timings is seen. Ignition timing has a significant effect on cylinder peak pressure and temperatures and thus on the NO_x emissions [33]. Retarding the ignition timing reduces NO_x emissions and it is therefore interesting that the maximum power and efficiency are seen for retarded ignition timings. In section 6.1.1.1 below the results of the corresponding emission measurements are presented. It is shown how the NO_x emission may be reduced significantly by retarding the ignition timing.
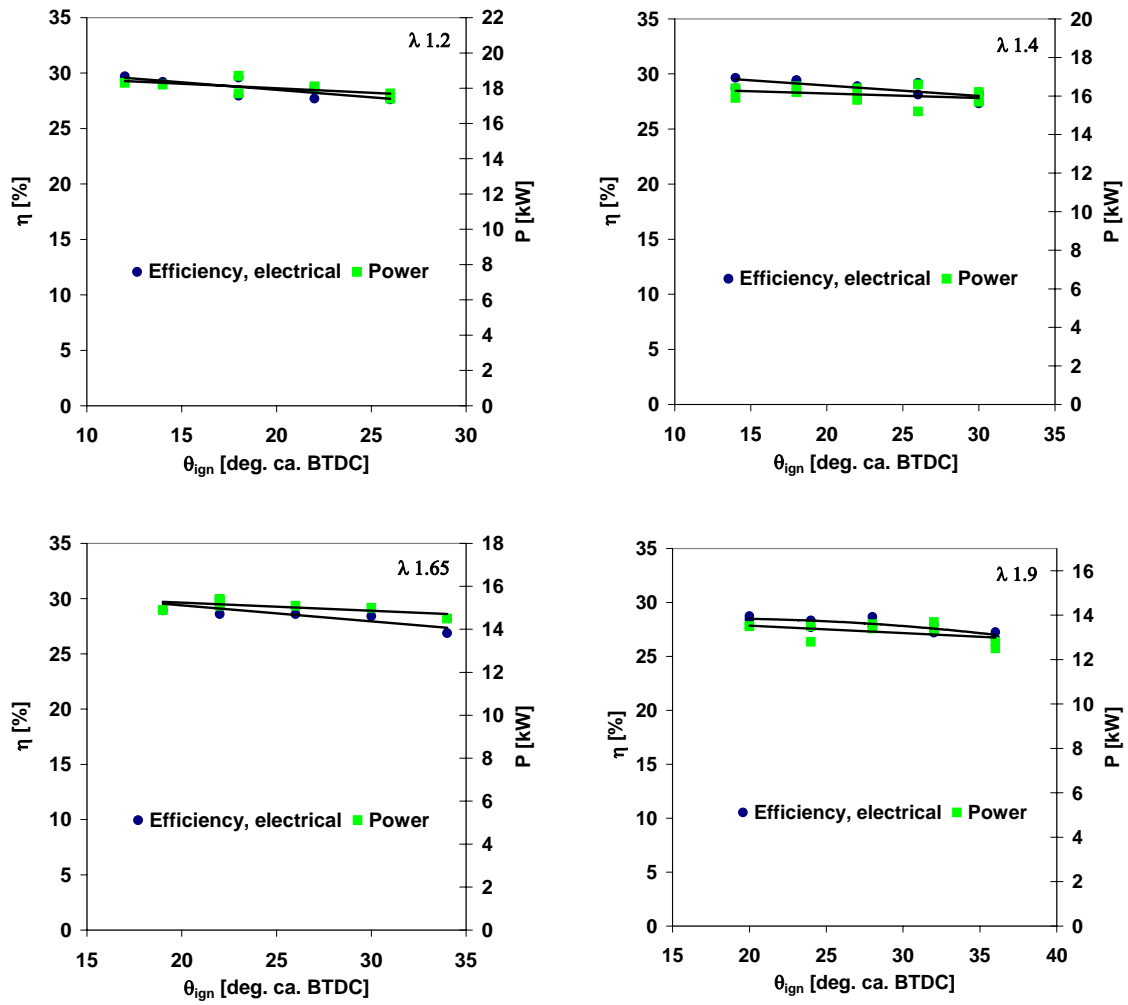
Figure 5.3 Power and electrical efficiency characteristics for producer gas operation with varying ignition timing.

6 EMISSIONS

In following sections extensive emission measurements will be presented. The main emphasis will be put on the standard emissions CO and NO_x and less on unburned hydrocarbons (UHC). The UHC emission is of less interest for engines operating on producer gas since the contents of hydrocarbons generally are relative low, cf. section 4.1. Additionally the emission of polynuclear aromatic hydrocarbons (PAH), aldehydes and laughter gas (N_2O) has been investigated. Additional information regarding emissions can be found in Appendix I, II, III, IV, V and VI.

6.1 Standard emissions CO/NO_x/UHC

The measurements of the emissions given in this section are expressed as mg per normal m^3 at a reference oxygen content of 5 Vol.% in the exhaust gas, (mg/Nm^3 @ 5% O_2). This unit complies with the emission regulations in the EU for stationary engine application [30, 32]. The following is an example of the definition of the unit for CO emissions as given by the Danish authorities [32]:

1 ppm CO = 1.25 mg/Nm^3 CO (at 0 ^{o}C and 101325 Pa)

$$C_{ref} = \frac{21 - O_2\%_{(ref)}}{21 - O_2\%_{(measured)}} C_{measured}$$
  Equation 6.1

C_{ref} emission concentration at the reference O_2% [mg/$Nm^3_{(ref)}$]

$C_{measured}$ measured emission concentration [mg/$Nm^3_{(ref)}$]

$O_2\%_{(ref)}$ reference O_2% [Vol.%]

$O_2\%_{(measured)}$ measured O_2% [Vol.%]

CO emissions from engines operating on producer gases are generally high, especially at lean conditions (λ>1.5) where the emissions exceed the regulated limits significantly. As producer gases only contain small amounts of hydrocarbons it is not possible that the high emission of CO can originate from incomplete combustion of hydrocarbons. The main contributor, especially at lean conditions, is the emission of unburned fuel-CO (UCO) (see section 6.1.1.2 and **Appendix V** and **Appendix VI**).

Modern gas engines are operated as lean burn engines ($\lambda\sim$2.2-2.4). These engines are turbo charged and a lean burn approach is necessary in order to keep the NO_x emissions below the regulated limit. Turbo charging is applied to increase power output from the engine. When operating an engine very lean a governing factor concerning emission of unburned fuel is bulk quenching [33, 34]. This means that the flame extinguishes in the bulk gas before the combustion is completed. Since producer gases only contain a minor amount of methane the emission of UHC from lean combustion is not significant. The CO content of producer gas on the other hand is 15-35% on a dry volume basis. This means that the major unburned emission from producer gas combustion will be CO. Another contributing factor is fuel being trapped in crevices in the combustion chamber where the propagating flame cannot penetrate into during the combustion process. The fuel trapped in the crevices will flow back into the combustion chamber during the expansion stroke where it will be oxidised if the temperature is sufficiently high [35]. Because the post oxidation occurs at relatively low temperature the combustion efficiency will be low, and therefore some fuel-CO will escape unburned.

High CO emission from gas engines fuelled by producer gas is a concerning problem in the struggle to make biomass gasification for heat and power production a success. The existing regulations concerning CO emissions from producer gas engine based power plants in most EU countries are so limited that no plant could uphold regulations without extra emission reducing equipment (see **Appendix V** and **Appendix VI**). In Denmark though, a new regulation has been introduced, specific for engines operating on biomass producer gas. In this regulation, the limit for CO emissions is 3000 mg/Nm^3 at 5% O_2 (for plants with an electrical output higher than 120 kW) [36].

NO_x emissions from engines are in general formed by a reaction between nitrogen and oxygen (usually defined as thermal NO_x). This reaction is strongly dependent on temperature, and NO_x emissions are therefore high for fuel rich combustion ($\lambda\approx$1) and low for fuel lean combustion [33]. As mentioned in section 4.3.3, producer gas may contain significant amounts of

NH_3 which, when combusted, may contribute significantly to the NO_x emissions (usually defined as fuel-NO_x).

The regulated limit for NOx emissions from new gas engine based power plants in Denmark is 550 mg/Nm^3 at 5% O_2 [36].

6.1.1 Average emissions and emission characteristics

The engines from the Güssing and the Harboøre plants are new large scale turbo charged lean burn gas engines from GE-Jenbacher, while the engine from the Viking plant is an older natural aspirated Deutz-MWM engine (see section 2.2 and 3). Table 6.1 shows the emissions from the engines at the three plants. It can be seen that the CO emission from the Viking engine is about the same as the other two despite the fact that the Viking engine is operated at lower λ than the other two. This indicates that the other two engines have better combustion efficiency, as would be expected. The engine at the Güssing plant has the highest CO emission of the three engines corresponding to the high CO content producer gas from the plant (see section 4.1). The Harboøre and Viking the plant meets the regulation in Denmark concerning both NO_x and CO.

Table 6.1 Examples of emissions from the different plants

	Harboøre [14]	Güssing [37]	Viking
NO_x [mg/Nm^3 @ 5% O_2]	400	700	200
CO [mg/Nm^3 @ 5% O_2]	1500	2000	1900
UHC [mg/Nm^3 @ 5% O_2]	6	-	40
λ [-]	2.2	2.2	1.8

The NO_x emission from the Viking engine is lower than for the two other plants despite the lower operating λ range. This is due to the turbo charging of the two other engines. However the NO_x emissions from the Güssing plant are almost twice as high as for the Harboøre plant due to the high NH_3 content in the producer gas (see section 4.3.3). Since the engines from the two plants are of similar configuration and design and the operating λ is the same, it is apparent that half of the Güssing NO_x emission is fuel-NO_x originating from NH_3 oxidation.

For the UHC emission it is notable that the Viking engine emits more than the Harboøre engine. The opposite would be expected since the Harboøre engine operating λ is higher than the Viking engine. This is due to the better combustion efficiency of the Harboøre engine caused by turbo charging.

In Figure 6.1 below emission data from one of the engines at the Harboøre plant is shown. The figure illustrates the relationship between emissions and load for a large scale lean burn turbo charged engine. Complying with NO_x and CO regulations is apparently not a problem for engine operation on Harboøre gas.
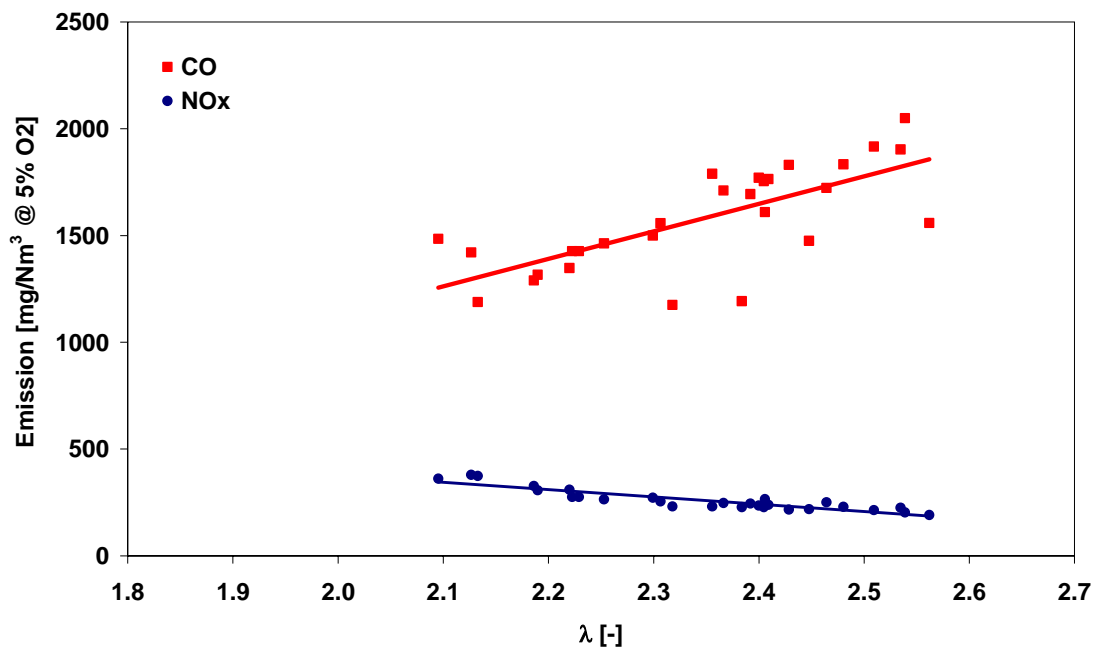
Figure 6.1 Emissions from one of the engines at the Harboøre plant.

6.1.1.1 Dependency on air-fuel ratio and ignition timing

In the following measurements of emission dependency with regards to λ and the ignition timing for the Viking engine are presented. As described in section 5.1 experiments have been conducted with the aim of investigating the influence of ignition timing on the performance and emissions for producer gas operation. For the data depicted in Figure 6.3 to Figure 6.6 each measurement point represents the average emission of about 30 minutes of operation. During the experiments the engine was kept at constant λ by the plants control system (see section 2.3). As shown in Table 5.2 it was possible to achieve relatively consistent gas conditions during the experiments. The

importance of consistent gas conditions is illustrated by Figure 6.2. The figure shows how the NO_x emission may vary with varying LHV of the producer gas. This relationship is also a justification for using average values to describe the trends in the results from the experiments.
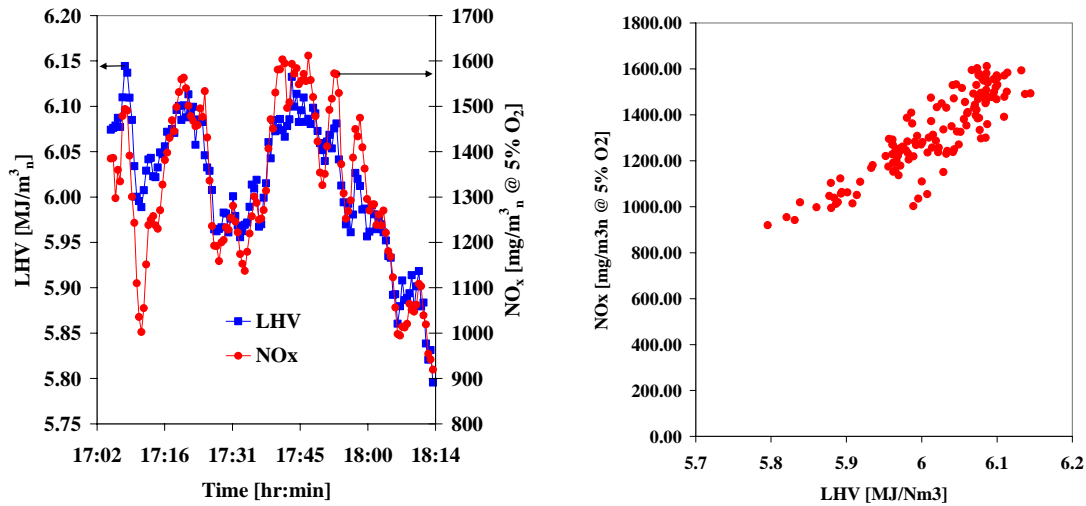

Figure 6.2 The relationship between NO_X emissions and LHV for 137 consecutive measurements, λ=1.4.

Figure 6.3 to Figure 6.6 below show the results of the emission measurements corresponding to the performance measurements presented in Figure 5.3. It can be seen that for retarded ignition timings the NO_x emissions are low, while the CO emissions are high. A slightly stronger dependency is seen for the NO_x emission to ignition timing than for CO. This trend is seen for all load conditions except for λ=1.2. The results show that NO_x emissions may be controlled by retarding the ignition timing but this will increase the CO emissions.
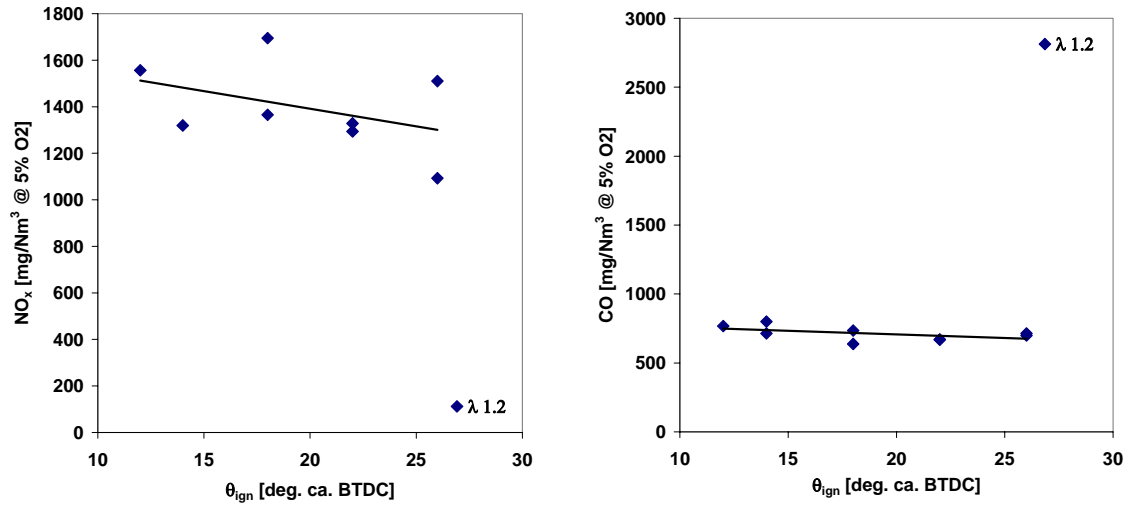
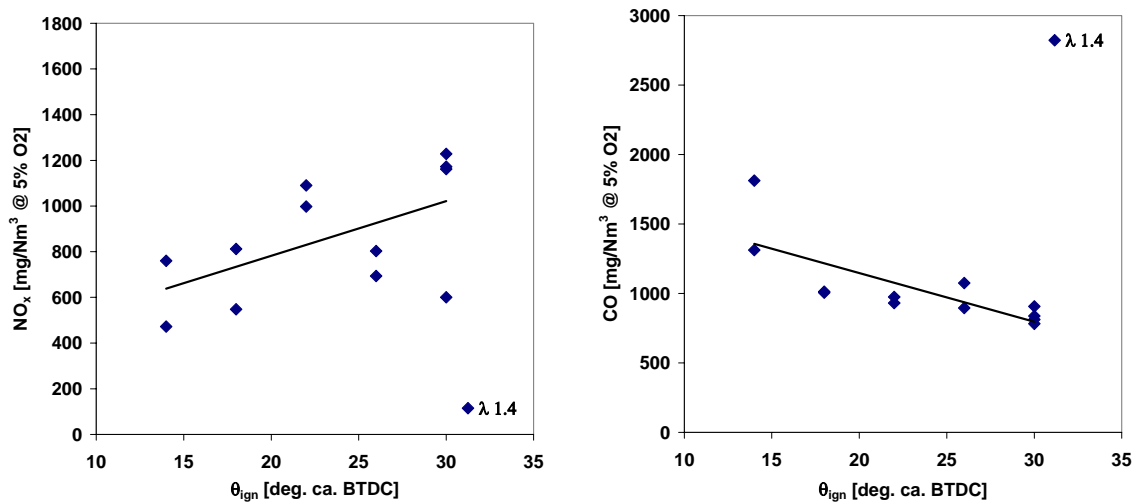**Figure 6.3 NO$_x$ and CO emissions depicted as a function of ignition timing for λ=1.2.**

Figure 6.4 NO$_x$ and CO emissions depicted as a function of ignition timing for λ=1.4.

Figure 6.7 shows the NO$_x$ and CO emissions for two different engine operation approaches; one where the ignition timing was adjusted for minimum CO emissions and one where the ignition timing was adjusted for minimum NO$_x$ emission. It is seen that the minimum CO approach results in significantly higher NO$_x$ emissions than the minimum NO$_x$ approach. On the other hand the CO emissions are higher for this approach, but still below the emission limit.
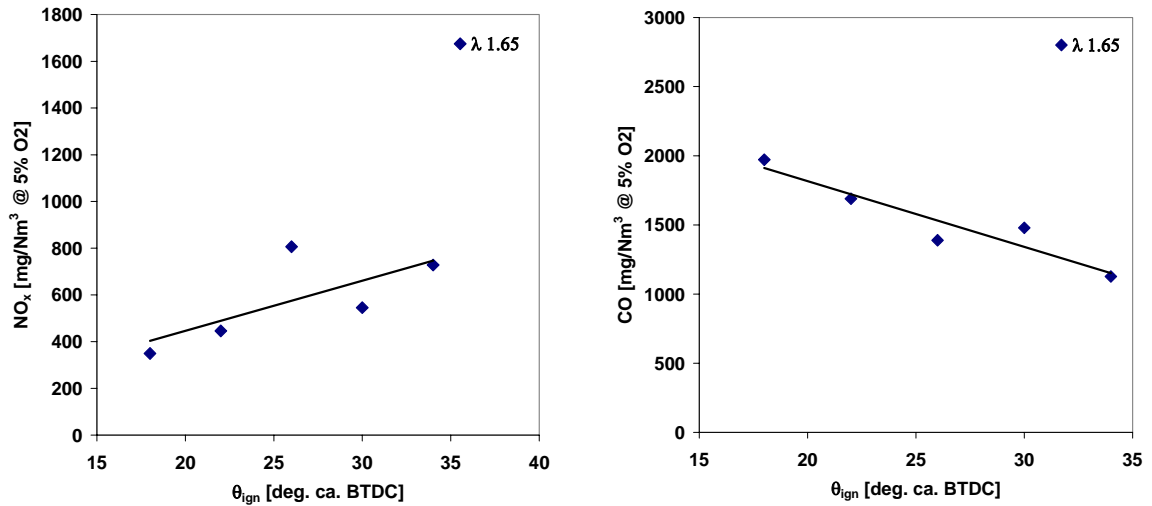
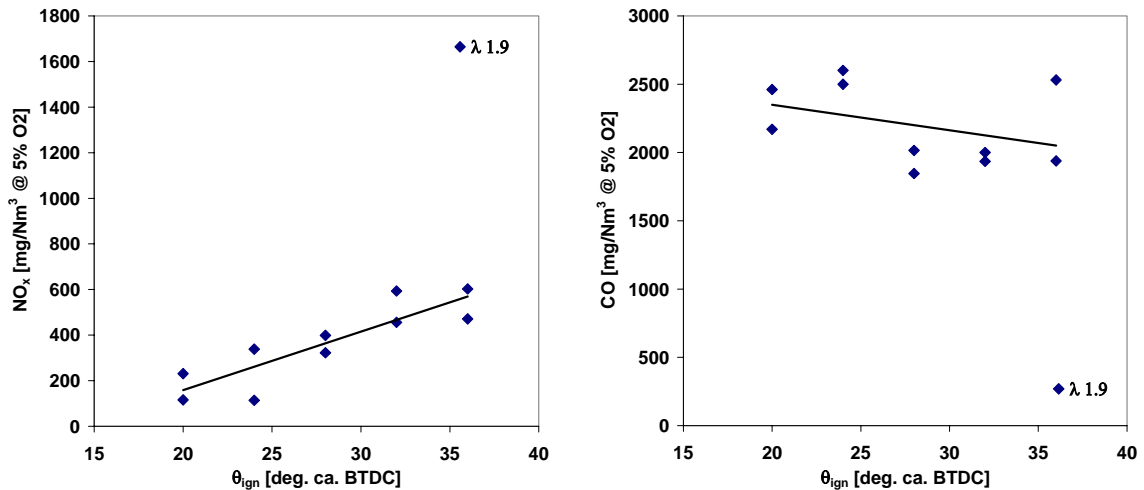**Figure 6.5 NO$_x$ and CO emissions depicted as a function of ignition timing for λ=1.65.**

Figure 6.6 NO$_x$ and CO emissions depicted as a function of ignition timing for λ=1.9.

Figure 6.7 indicates that it is possible to reduce the operating λ from λ=1.8 to below λ=1.6 and still comply with the emission regulation. Looking at the measurements for λ=1.65 as depicted in Figure 6.5 it is seen that for an ignition timing of approximately 30° before top dead centre the NO$_x$ emission is close to the limit. The measurements show NO$_x$ emissions may be reduced significantly by adjusting the ignition timing whiteout reduction of power output and efficiency, cf. Figure 6.8 and Figure 5.3.
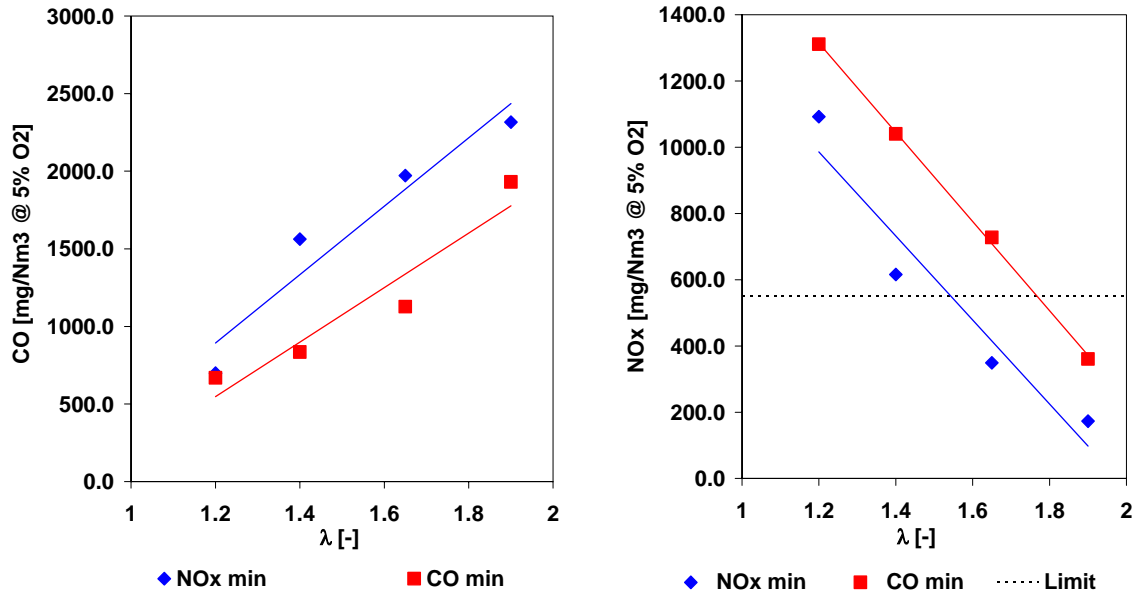
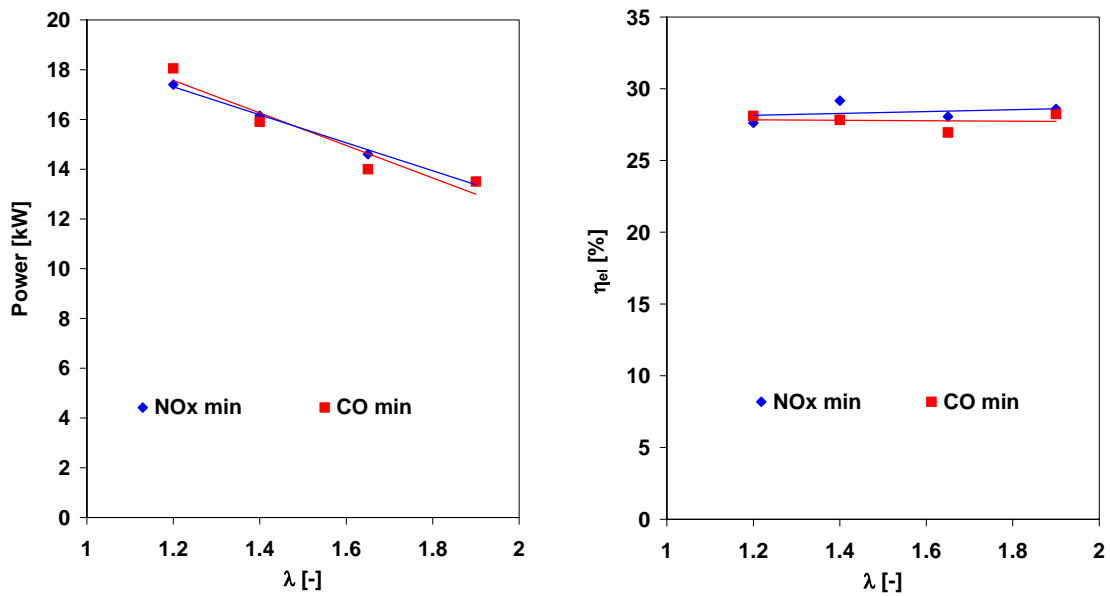**Figure 6.7 The dependency of NO$_x$ and CO emissions on λ for CO minimum and minimum NO$_x$ operation.**

Figure 6.8 The dependency of power and efficiency on λ for minimum CO and minimum NO$_x$ operation.

6.1.1.2 Slip of fuel

The emission of hydrocarbons is a slip of unburned fuel (UHC) [31, 33, 34, 35]. If, as stated earlier, the emission of CO is also an emission of unburned fuel then the slip of UCO and UHC (CH_4) from engines operating on producer gas should be of the same order. The slip of fuel is calculated as the following:

$$Slip_{CO} = \frac{\dot{n}_{CO\_out}}{\dot{n}_{CO\_in}} \cdot 100\% \qquad Slip_{CH_4} = \frac{\dot{n}_{CH4\_out}}{\dot{n}_{CH4\_in}} \cdot 100\% \qquad \textbf{Equation 6.2}$$

$\dot{n}_{CO\_in}$ mole flow of CO in to the engine [mole/Nm^3_{gas}]

$\dot{n}_{CO\_out}$ mole flow of CO out of the engine [mole/Nm^3_{gas}]

At λ=1.4 the slip of CO is 1.2 and the slip of CH_4 is 0.8, cf. Figure 6.9. The slip of CO and CH_4 are of the same order of magnitude. The slightly higher slip of CO would be expected, since some CO will originate from incomplete oxidation of CH_4. At lean conditions the temperature at the end of the combustion cycle can get so low that CH_4 will not be oxidised completely to CO2, but only to CO, resulting in a relatively higher CO emission, cf. Reaction 2. This is confirmed by the trends seen in Figure 6.11.
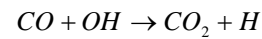
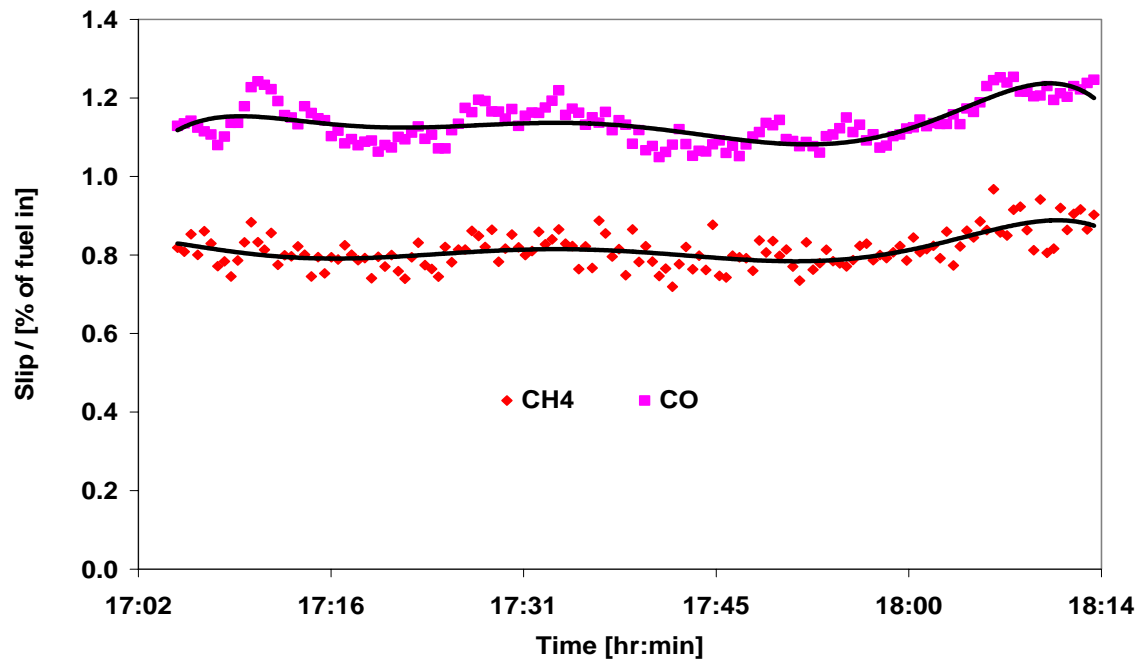$$CO + OH \rightarrow CO_2 + H \qquad \textbf{Reaction 2}$$

Figure 6.9 The percentage of the fuel components CO and CH$_4$ that passes unburned through the engine, λ=1.4.

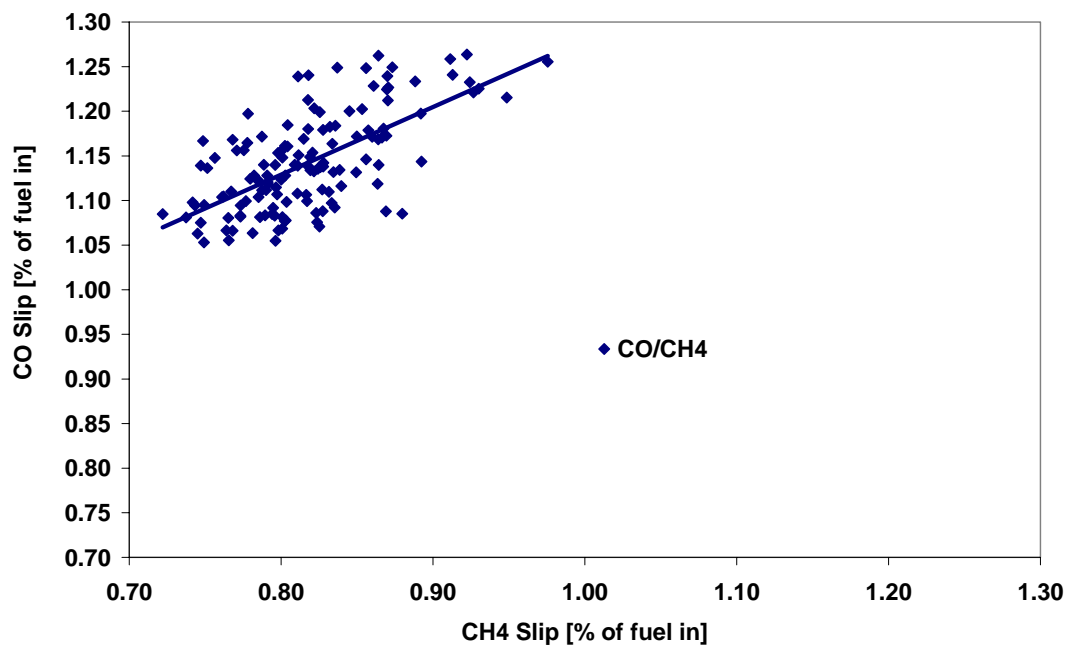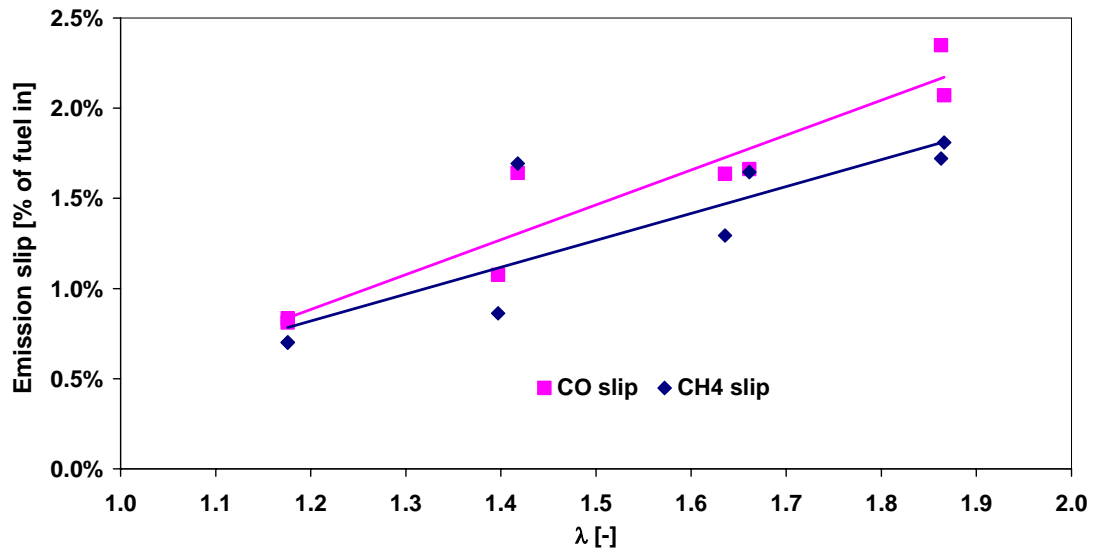**Figure 6.10 The correlation between the slip of the fuel components CO and CH$_4$, λ = 1.4.**

Figure 6.11 The relationship between λ and the slip of fuel.

The measurements depicted in Figure 6.9 and Figure 6.10 show the distinct correlation between the slip of CO and CH_4. This clarifies that the emission of CO from the engine is an emission of unburned fuel-CO.

6.2 Emission of Polynuclear Aromatic Hydrocarbons

The limitation of the emission of PAH is significant since more than 25 PAH compounds are known or suspected to be carcinogenic.

Formation of PAH in gas engines may originate from several sources:

- Organic aerosols
- Higher hydrocarbons in the fuel gas
- Engine lubricant

Several factors control the formation of PAH. If the engine is running fuel-rich ($\lambda<1$) aerosols and gaseous higher hydrocarbons are not oxidised completely but pyrolysed, and tars and PAH can be formed, especially phenols are known to be precursors for PAH [38] (see also **Appendix II**).

A second factor is the gas trapped in crevices in the combustion chamber. For fuel-rich operation the gas flowing out from the crevices during the expansion stroke only sees hot exhaust gas and no oxygen. Partial oxidation and pyrolysis of the fuel may occur and PAH can be formed.

A third factor contributing to PAH formation is partly combustion/pyrolysis of lubricant volatilize from the cylinder walls lubricant film. This may happen if the flame propagation reaches the cylinder walls before it is extinguished.

Since nearly all modern stationary gas engines are lean burn engines, formation of PAH is not likely to take place in these engines. Measurements made in Denmark on stationary gas engine power plants operating on both biogas and natural gas confirm this. The measurements showed emissions of 0.01-0.07 μg benzo[a]pyrene equivalent/m^3_n @ 5% O_2 [39] which is 70-200 times lower than the maximum recommended value, cf. Table 6.2.

Table 6.2 shows the results of the PAH measurements from the Harboøre and Viking plants. The results are given as a benzo[a]pyrene-equivalent value for the total PAH emission (see **Appendix III** and **Appendix VI** for more information).

For the Viking plant it was not possible to detect any PAH components in the exhaust gas of the engine. However the analysis was carried out with a fairly high detection limit, meaning that the given value for the benzo[a]pyrene-equivalent PAH emission is a worst case value calculated from the detection limits for each PAH component (see **Appendix VI**). It can thus be concluded that the emission from the engine is below 1.95 μg benzo(a)pyrene-equivalent/m^3_n @ 5% O_2. This is still several times below the regulated value, cf. Table 6.2.

Measurements from the Harboøre plant showed that the emission of PAH is very low and consists mainly of naphthalene and phenanthrene (naphthalene is not among the 15 PAH selected by the U.S. environmental protection agency (EPA) as being suspected carcinogens). From Table 6.2 it is seen that again the benzo[a]pyrene-equivalent PAH emission is significantly lower, about 22 times, than the recommended emission limit in Denmark. The measurements also show that the PAH present in the producer gas before the engine is reduced. The average reduction of the PAH components is about 300 times when the dilution of the exhaust gas through combustion air is taken into account (see also **Appendix VI**).

Table 6.2 The Benzo(a)pyrene-equivalent PAH emissions from the gas engine at the Viking and Harboøre plants [40] operating on producer gas.

PAH [$\mu g/m^3_n$, dry]	Harboøre plant before the engine	Harboøre plant after the engine	Viking plant after the engine	PAH regulation in Denmark
Benzo[a]pyrene-equivalent at 5% O_2	161.3	<0.23	<1.95	5

Experimental lab-scale investigation regarding the formation of PAH emissions caused by the presence of the light tar compounds phenol and guaiacol in producer gas showed a significant increase of PAH in the exhaust gas of the test engine due to phenol and guaiacol when compared to reference measurements made with no tar addition. The measurements showed that approximately 90% of the PAH detected was vapour phase. For the particulate bound PAH it was shown that there was no increase in PAH due to tar addition. On the contrary a significant decrease in particulate bound PAH was observed for phenol addition (see **Appendix II** for more information).

6.3 Aldehydes and Laughter gas (N_2O)

The emission of aldehydes and especially formaldehyde is of particular interest both due to their photochemical reactivity in ozone formation and suspected carcinogenicity. Formaldehyde (CH_2O) is formed as an intermediate of hydrocarbon combustion and the emission is thus a product of incomplete combustion. In Table 6.3 the measurements of the emissions of aldehydes are shown for the Viking engine operating on both producer gas and natural gas. The measurements shows that the emission of formaldehyde was 19 times lower for producer gas operation than for natural gas operation Comparing the fuel flows to the engine show that for producer gas operation the hydrocarbon flow was about 15 times lower than for natural gas operation, for the same fuel/air equivalence ratio (λ). This indicates that the combustion process in this engine is more efficient for producer gas than for natural gas.

The emission of laughter gas (N_2O) is important because this compound is a strong greenhouse gas with a global warming potential of 296 [41], even though there is no regulation regarding the emission. The measurements

show that the emission of N_2O was 2.4 times lower for producer gas operation than for natural gas operation (see Table 6.3).

Table 6.3 Aldehydes and N_2O emissions from the Viking engine operating on producer gas and natural gas.

Fuel gas	Producer gas	Producer gas	Producer gas	Natural gas	Natural gas
Formaldehyde [$\mu g/m^3_{n,t}$]	1669	2014	2431	42765	35822
Acetaldehyde [$\mu g/m^3_{n,t}$]	271	259	307	976	810
Acrolein [$\mu g/m^3_{n,t}$]	6	4	5	220	201
Propanal [$\mu g/m^3_{n,t}$]	21	25	32	16	9
Acetone [$\mu g/m^3_{n,t}$]	360	369	369	268	104
Butanal [$\mu g/m^3_{n,t}$]	5	4	16	<1	<1
Pentanal [$\mu g/m^3_{n,t}$]	<1	<1	<1	<1	<1
Haxanal [$\mu g/m^3_{n,t}$]	14	<1	<1	<1	<1
Benzaldehyde [$\mu g/m^3_{n,t}$]	24	16	21	1	3
N_2O [vol. ppm]	<0.5	2.3	3.3	7.3	6.2

7 COMBUSTION ANALYSIS

Combustion analysis has been carried out applying a well documented three-zone model developed by Jensen [42]. The model is a two-zone heat release model which takes into account the effect of crevices on the combustion, thus three zones [34, 35, 42].

The model is a thermodynamic model applying the first law of thermodynamics for the burned and unburned zones and mass and volume balance for the system made up of the combustion chamber (see Figure 7.1). The following assumptions are made [42]:

- No conduction of heat between the zones

- For the residual gas fuel and air are mixed perfectly

- All gases are treated as ideal gases

- The pressure in combustion chamber is uniform at any instant

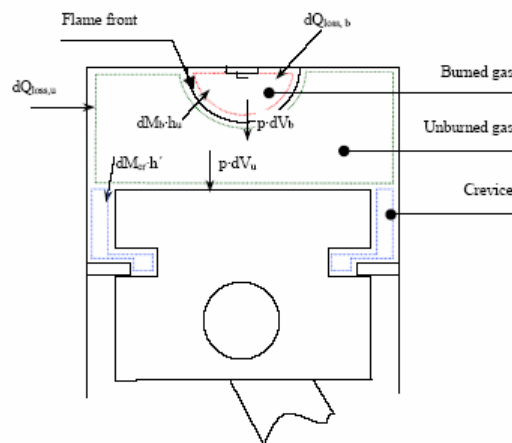- The crevices in the combustion chamber are modeled as one crevice containing only unburned gas

Figure 7.1 The combustion chamber, from [34, 42]

The heat release analysis is based on recorded pressure-time history of the combustion cycle, in order to investigate the combustion process for producer gas operation. The 3-zone heat release model has been validated by using a 1-zone engine model to generate pressure traces. Assuming zero heat loss for both models the mass burned fraction determined by the 3-zone model from the 1-zone model pressure trace has to reach unity for the given combustion period.

In cylinder pressure measurements series were made for 4 different λ-values. For each λ-value pressure traces have been measured for 44 consecutive combustion cycles. One pressure trace consists of 1440 pressure

measurements which equals to 2 measurements per degree crank angle. A Kistler 6031 piezoelectric pressure transducer coupled with a Kistler 5015 charge amplifier was used for the in cylinder pressure measurements. The measurement timing was controlled by use of an encoder from Scancon. The encoder triggers the measurement and gives a measurement frequency of 720 measurements per revolution. The measured pressure signals were recorded using data acquisition hardware and software (Lab-View) from National Instruments. A description of the methods for gas composition measurements is given in **Appendix IV**.

Table 7.1 below provides the gas composition and LHV of the producer gas corresponding to the pressure measurements. It can be seen that there are significant variations in gas composition and thus LHV for the different λ-values. These variations are mainly due to the fact that the gasifier was operating on a wood fuel with a significantly varying moisture content and that the gasifier control system was not yet tuned for this fuel. The variation in gasifier operation results in significant uncertainty for the LHV determination. Since the gas composition is varying it is difficult to determine the exact LHV corresponding to a specific pressure measurement series. These uncertainties will be reflected in the results from the heat release analysis and will have to be taken into account when comparing the measurements for the different λ-values.

From Table 7.1 it can be seen that power output is the same for the λ=1.9 and λ=2.2. This is due to the variations in the gas composition. The LHV_{mix} of the air-fuel mixture entering the engine is almost the same for the two λ-values. Even though there are significant variations in the gas composition the engine efficiency is very stable.

Table 7.1 The gas composition, LHV and engine performance corresponding to the pressure measurements.

λ [-]	1.4	1.6	1.9	2.2
CO [%]	14.0	14.4	15.4	16.0
H2 [%]	22.3	25.8	24.1	32.8
CH4 [%]	1.2	1.5	0.8	2.6
CO2 [%]	15.6	16.5	15.3	16.7
N2 [%]	46.9	41.8	44.3	31.9
LHV [MJ/Nm^3]	4.6	5.1	4.9	6.4
LHV$_{mix}$ [MJ/Nm^3]	1.6	1.4	1.0	0.9
P [kW]	13.2	12.6	11.1	11.1
$\eta_{electric}$ [%]	28	28	27	27

In Figure 7.2 the average pressure and the determined mass burned fraction (x_b) is depicted. It is seen that the highest final mass burned fraction is obtained for λ=1.4 and for λ=1.6. The slope of x_b is steepest for λ=1.6 indicating fastest combustion. That the slope is steeper than for λ=1.6 might be due to the higher H_2 content in the producer gas for this λ-value, which is also supported by the fact that the highest average maximum pressure is seen for λ=1.6, cf. Figure 7.2. The slope and final x_b are similar for λ=1.9 and λ=2.2 despite the difference in λ-value. This reflects the similar LHV$_{mix}$ for both λ-values and is supported by almost identical average pressure traces. The uncertainties regarding the determination of the exact LHV corresponding to a specific pressure measurement series will of course be reflected as uncertainties for the determination of x_b, but the results are in general well supported by the pressure measurements. The small difference in slope and final x_b for 1.4<λ<2.2 characterises producer gas as a god lean burn fuel.
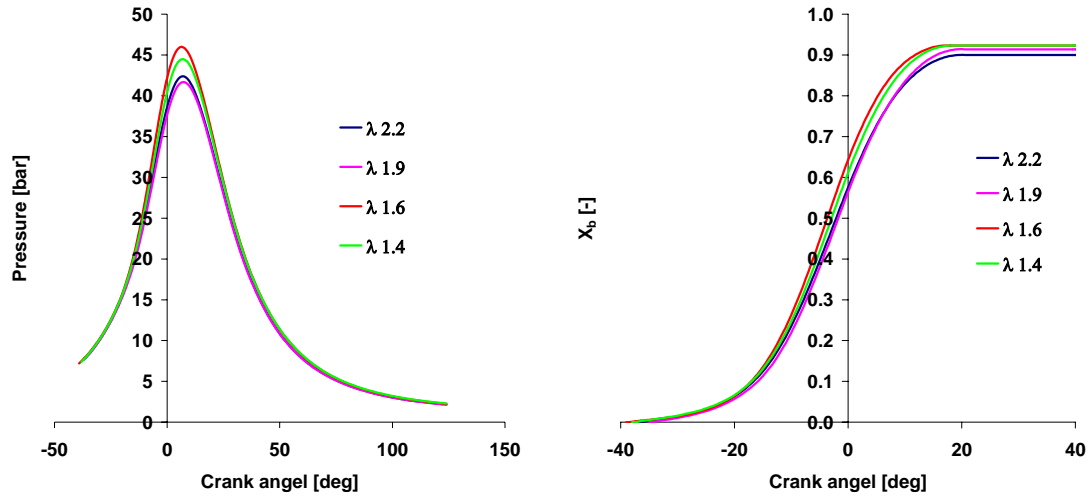
Figure 7.2 The average pressure and mass burned fraction, λ=1.4, 1.6, 1.9 and 2.2.

An important feature charactering the combustion properties of a fuel is the analysis of cycle to cycle variations.

In Figure 7.3 all measured pressure traces are depicted, and in Figure 7.4 the mass burned fraction determined from the pressure measurements are shown. As can be seen the variations x_b from cycle to cycle are of the same order as the variations seen for varying λ for the average x_b. In order to quantify the cyclic variations the term coefficient of variation (COV) is used. The coefficient of variation of a property is calculated as:

$$COV_y = \frac{\sigma_y}{\bar{y}}$$

Equation 7.1

Where σ_y is the standard deviation and $\bar{y}$ is the average value of *y*.

The COV for the indicated mean pressure (IMEP) and for x_{b_max} are important measures when characterizing the combustion process [42, 43]. From Figure 7.5 it can be seen that there is practically no dependency of the COV for either of the two parameters with regards to λ. This is very different from what is seen for natural gas combustion, where the COV for both IMEP and x_{b_max} increases with increasing λ [35, 42]. This emphasizes the good lean burn properties of producer gas.
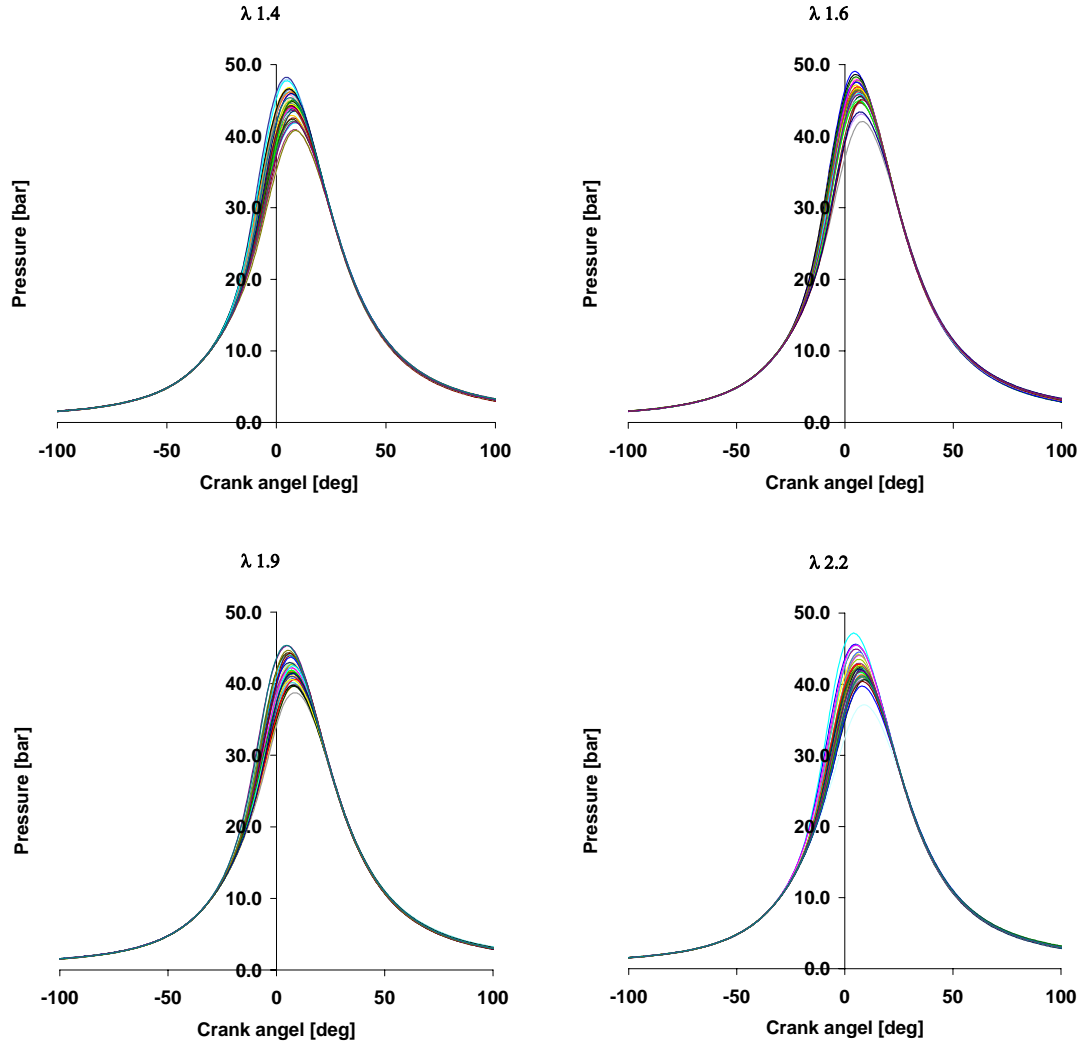
53

Figure 7.3 Measured pressure traces for 44 consecutive combustion cycles for λ=1.4, 1.6, 1.9 and 2.2.

Table 7.2 presents a statistic analysis of when the mass burned fraction reaches the maximum value (x_{b_max}). It is of interest to know the deviations of x_b because in the fast combustion cycles there will be an increased tendency of knocking which means that it is the fastest combustion cycles which determine the upper compression ratio for a chosen fuel. For the slow combustion cycles there is a risk that the combustion is incomplete, and the emission of unburned fuel will thus increase [34].

It is seen that the average timing ($\theta_{Average}$) for which x_{b_max} occurs advances for the low load conditions (λ= 1.9 and 2.2) compared to high load (λ= 1.4 and 1.6), correspondingly the standard deviation (θ_{stdev}) increases, c.f. Table 7.2. Comparing λ=1.4 and 1.6, the timing for the fastest x_{b_max} (θ_{min}) is stable, while the slowest x_{b_max} (θ_{max}) is seen for λ=1.4. This could be due to the lower H_2

contents of gas composition for this measurement series. This is also reflected in a higher standard deviation (θ_{stdev}) for λ=1.4. Comparing λ=1.9 and 2.2 it is notable that both the fastest and slowest combustion cycle is seen for λ=2.2. This may reflect the high H_2 and CH_4 contents of gas composition for this measurement series, meaning that a high H_2 contents favors fast combustion while high CH_4 may lead to slower combustion.
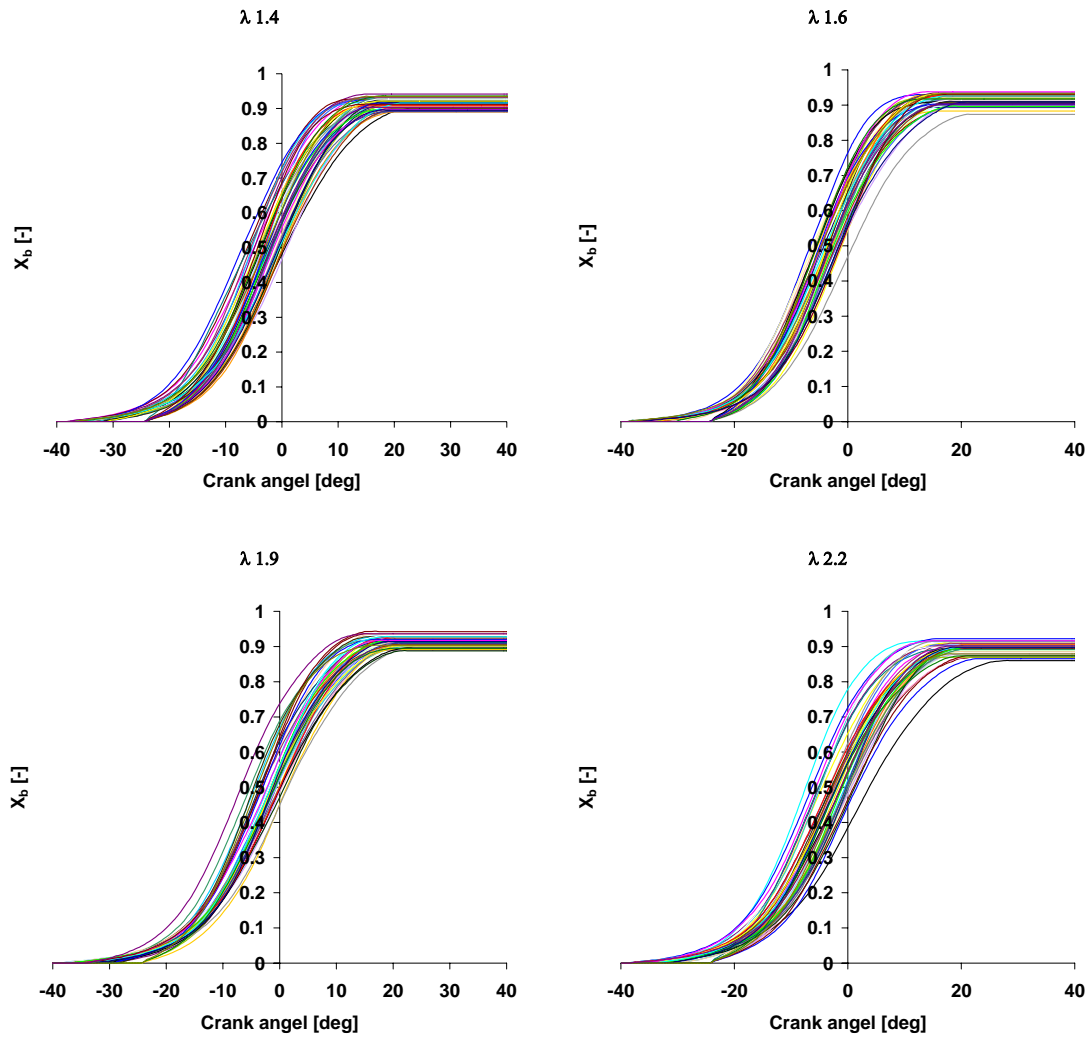

Figure 7.4 Mass burned fraction for 44 consecutive combustion cycles for λ=1.4, 1.6, 1.9 and 2.2.

Table 7.2 The average, max, min and standard deviation of crank angle position at which final x_b is reached.

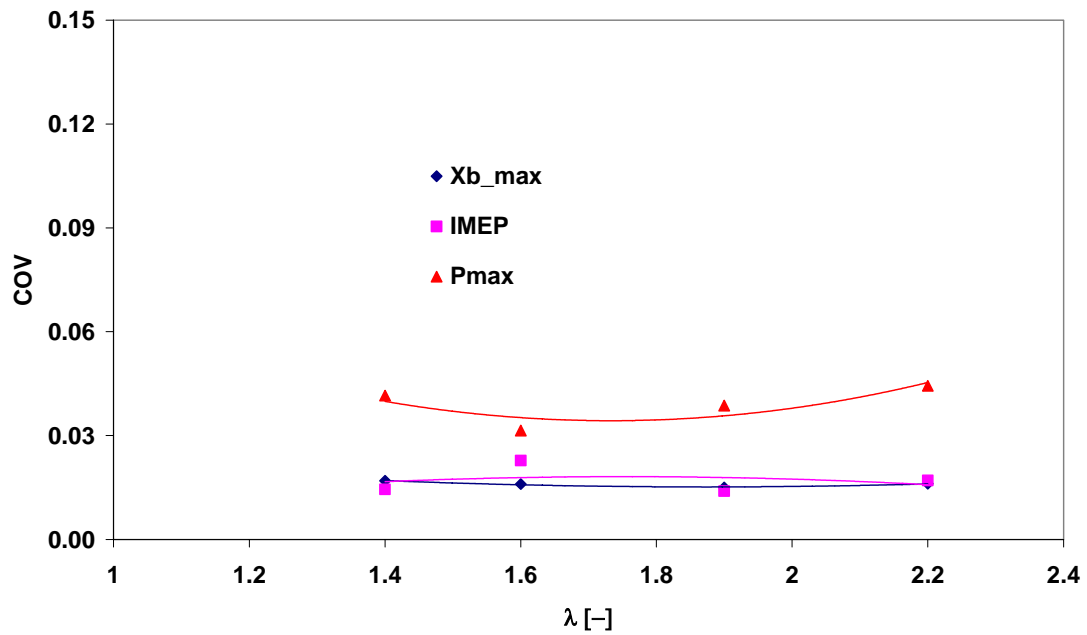| λ [-]	1.4	1.6	1.9	2.2
$\theta_{Average}$ [deg. Crank angle ATDC]	18	17	21	20
θ_{max} [deg. Crank angle ATDC]	25	22	25	29
θ_{min} [deg. Crank angle ATDC]	13	13	16	14
$\theta_{stdev.}$ [deg. Crank angle ATDC]	2.4	2.0	3.9	4.3

Figure 7.5 The COV of x_{b_max}, IMEP and p_{max}.

The low level of COV for all λ-values and the absence of extreme combustion cycles indicate that producer gas may be applied in engines with high compression ratio. This is confirmed by lab-scale experiments presented in **Appendix I** and in **Appendix II** where a one cylinder test engine was operated on synthetic producer gas with a compression ratio of 16:1 over a wide range of λ-values. Results supporting this are also seen in the literature Sridhar [44] has reported both experimental and model results for producer gas operation with a compression ratio of 17:1, and Hernandez et al. [45] have made chemical kinetic modeling of the auto ignition delay time of producer gas, showing the potential of producer gas to reduce the knock tendency in spark ignition engines despite the high H_2 content of the producer gas.

Unfortunately it has not yet been possible to repeat the pressure measurements on the engine with natural gas fuel. This would have given a more accurate comparison between producer gas and natural gas operation. The plan is to continue this part of the work in succeeding projects.

Originally it was planned that the combustion analysis should have been conducted with pressure measurements corresponding to emission measurements presented in section 6.1.1.1 where both the effect of varying λ and ignition timing was investigated. Pressure measurements were made during the experiments but the following heat release analysis exposed errors due to the hard wear that could not be detected during the measurements. All the measurements made had to be discarded and new measurement equipment had to be acquired.

8 ENGINE OPERATION EXPERIENCES

8.1 Deposits and engine wear

One of the main problems in the development of the technology has been the tar compounds present in the producer gas. The quantity of tars that some gasification systems generate may ruin internal parts of a modern gas engine. Even though novel gas cleaning systems are highly efficient, it must be expected that small quantities of tar will reach the engine. It is necessary to take the effects of these compounds on engine wear into account.

Tar formed from updraft gasification of biomass consists mainly of primary tar compounds, e.g. phenols and guaiacols (see section 4.3.1) [46, 38]. Primary tars are oxygen-rich and condensable compounds with a potential for formation of combustion chamber deposits (CCD) in gas engines [47].
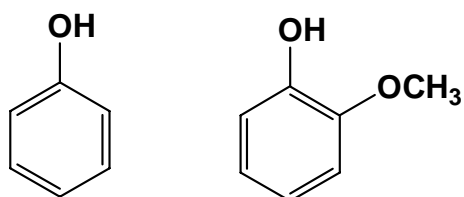
Figure 8.1 Chemical structures of phenol and guaiacol.

Investigations were made concerning the formation of CCD in SI gas engines fuelled by biomass producer gas. The main objective was to determine and characterise CCD caused by the presence of the light tar compounds phenol and guaiacol in producer gas from an updraft gasifier. The work was based on previous work regarding the assumption that phenol is a soot precursor and therefore could lead to CCD formation [38].

Table 8.1 An example of tar quantities in the raw and purified gas from an updraft gasifier [38].

| Compound	Raw Gas mg/Nm^3	Clean Gas mg/Nm^3
Phenol	898	25
Guaiacol	1500	29
Naphthalene	74	14
Phenanthrene	29	< 0.1
Pyrene	5.9	< 0.1

Experiments were conducted with a 0.48 litre one-cylinder high compression ratio SI engine fueled by synthetic producer gas. The engine was operated at a compression ratio of 16:1. Known quantities of tar compounds were added to the fuel gas and the CCD were examined. The result of pyrolysis-GC/MS analysis of the CCD from the engine experiments showed that the deposits could not be related to the additives. It was not possible to establish a connection between the deposits from the guaiacol engine experiments and the additive as was expected from laboratory experiments with guaiacol. It is assumed that the combustion chamber deposits are derived from the lubricating oil.

When compared to reference experiments with pure water addition, it was observed that formation of CCD was inhibited by the addition of phenol. Additional results from the investigation are given in **Appendix II**.

In order to inspect the internal parts of the Viking engine for formation of deposits, wear and corrosion, the engine heads have been removed several times between test-runs. As Picture 8.1 indicates no significant built up of deposits has been seen on either the piston top or the engine head. Likewise no corrosion or wear originating from the producer gas has been observed.

Picture 8.1 The engine and piston head of the engine at the Viking plant after 1100 hours of operation on producer gas.
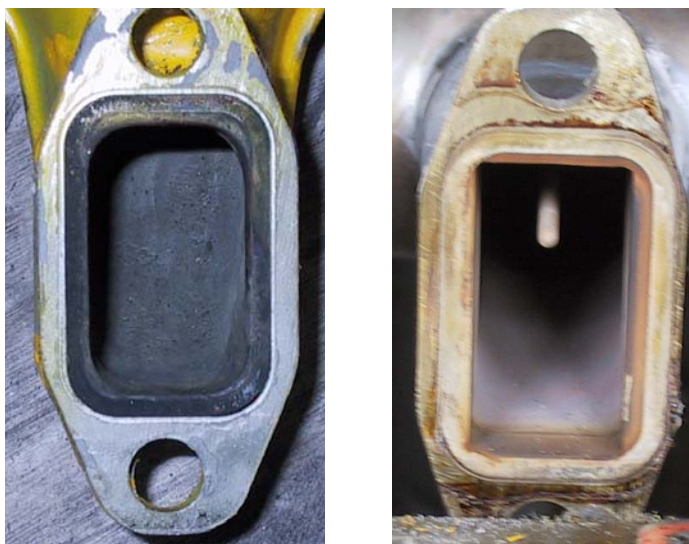
Picture 8.2 The intake and exhaust manifolds of the engine at the Viking plant after 1100 hours of operation on producer gas.

8.2 Engine Oil

In order to uphold long periods between engine services it is essential to maintain a good engine oil quality. Since the wood fuel contains both sulphur and chlorine in varying quantities special attention has to be paid to over acidification of the oil (TBN/TAN ratio). Also gas cleaning techniques can influence the gas quality with regards to pH. At the Güssing plant a change of the filter pr-coating material (see section 3.2) reduced the period between oil changes from 4000 operation hours to 1000 operation hours [26].

Especially the accumulation of chlorine in lubricant is of interest since experiences from the Harboøre plant have shown that chlorine is a problem regarding lubricant degradation. At the Harboøre plant significant amounts of methyl chloride (30 ppm) have been measured in the producer gas, and this has resulted in accumulation of organic chlorine in the engine oil (>500 ppm), this has lead to an accelerate degrading of the engine oil. The accumulated chlorine in the oil may react with hydrogen radicals and reform HCl which can corrode the internal parts of the engine.
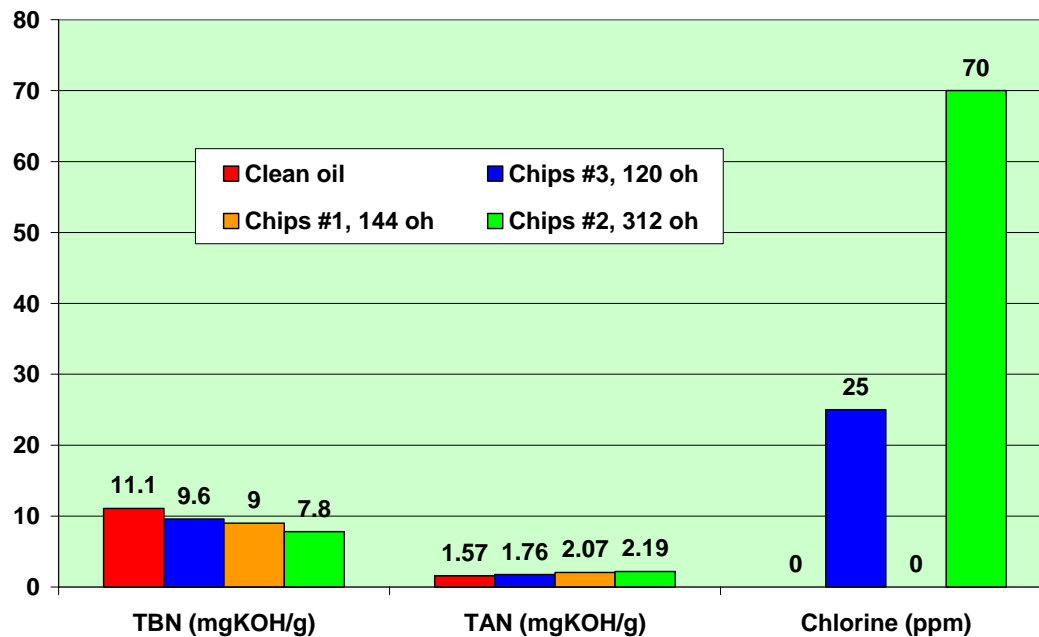
Figure 8.2 Analysis of engine lubricant

Analysis of the engine lubricant at the Viking plant was conducted in order to monitor any accelerated degrading of the lubricant due to the application of the producer gas. Figure 8.2 shows the total base number (TBN), the total acid number (TAN) and the chlorine contents of the oil from different analysis. It can be seen that the TBN is reduced over time (the limit is 4) while the TAN increases over time (the limit is also 4). The chlorine contents increases with time but it is also very dependent on the chlorine contents of the wood fuel, cf. Table 8.2.

Table 8.2

	Chips #1	Chips #2	Chips #3
Cl [wt. %]	0.063	0.140	0.200

 The conclusion from the oil analysis so far is, that the expected oil life time of the Viking engine is 600-800 hours depending on the chlorine contents of the wood fuel.

9 CONCLUSIONS

Investigations have been made in order to analyse and characterise the utilisation of biomass producer gas as a fuel for stationary gas engines in heat and power production. Data from three biomass gasification CHP plants have been analysed.

As a major part of the work carried out, 3200 hours of gas engine operation with producer gas from biomass as fuel has been conducted at the gasification CHP demonstration and research plant named Viking at the Technical University of Denmark. The Viking plant produces a producer gas with a very stable composition suitable for gas engine operation. Multiple measurements of the tar content showed that only 0.02-0.1 mg/Nm^3 of naphthalene could be detected in the raw producer gas. The energy balance for the plant shows a fuel to gas efficiency of 93%, a gas to electricity efficiency of 29% and an overall wood to electricity efficiency of 25%.

An investigation of the producer gas from the Viking plant and two other plants have shown that:

- Significant variation in gas composition and heating value are seen over time.

- Due to the low stoichiometric air/fuel ratio, the low heating value of producer gas does not equal low power output. At lean conditions producer gases may even present a power advantage compared to natural gas.

- The tar content in producer gases varies significantly from plant to plant, but in general tars are not a problem for the three plants investigated in this project.

- The contents of H_2S, COS and Cl may in some cases cause problems with accelerated degradation of engine oil.

- High concentrations of methyl chloride in the gas from low temperature gasification processes may give corrosion problems in the gas conditioning system and cause accelerated degradation of engine oil.

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Investigations of the performance characteristics for producer gas operation have shown that:

- Biomass producer gas is an excellent lean burn engine fuel. Operation of a natural aspirated engine has been achieved for $1.2<\lambda<2.8$ without significant reduction of engine efficiency.

- For varying load conditions practically no dependency of power and efficiency with regards to the ignition timing is seen.

Extensive emission measurements have shown that:

- In general NO_x emissions are not a problem for lean burn producer gas operation, except for producer gas with high concentrations of NH_3.

- The present regulations concerning CO emissions from gas engine based power plants in most EU countries are so low that no plant could uphold regulations without extra emission reducing equipment. The exception is Denmark were a new regulation has been introduced, specific for engines operating on biomass producer gas.

- The high CO emission from producer gas engine operation is primarily 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.

- By controlling the ignition timing NO_x emissions may be reduced significantly without reduction of load and efficiency.

- Measurement showed that there is no relation between a high CO emission and high PAH emission for engines operating on biomass producer gas. Measurements of PAH emissions corresponding to a CO emission of 2800 mg/Nm^3 @ 5% O_2 were about 22 times lower than the recommended maximum emission limit in Denmark.

- Measurements of the PAH emission from the engine at the Viking plant showed that no compounds could be detected.

- Compared with emissions from engines operating on natural gas, emissions of aldehydes were seen to be very low, while the emission of N_2O was measured to be at an equivalent level.

Analysis of the combustion process for producer gas operation by applying a heat release model showed that:

- A constant low level of cyclic variations for a wide range of λ-values and the absence of extreme combustion cycles characterise producer gas as a god lean burn fuel and indicate that producer gas may be applied in engines with high compression ratio.

Experimental investigations were made concerning the formation of combustion chamber deposits (CCD) and PAH in SI gas engines fuelled by producer gas. The main objective was to determine and characterise CCD and particulate matter formation caused by the presence of the light tar compounds phenol and guaiacol as seen in producer gas from an updraft gasifier. The experiments showed that:

- No increase in particulate matter (PM) due to the presence of phenol and guaiacol in the producer gas despite the fact that tar concentrations in the experiments were an order of magnitude higher than the concentration measured in purified gas from an updraft gasifier.

- A significant increase of PAH in the exhaust gas of the test engine due to phenol and guaiacol when compared to reference measurements made with no tar addition.

- Approximately 90% of the PAH detected was vapour phase based.

- For particulate bound PAH no increase in PAH was seen due to the tar addition. On the contrary a significant decrease in PAH was observed for phenol addition.

- Combustion chamber deposits (CCD) could not be related to the two tar components.

- It was observed that formation of CCD was inhibited by the addition of phenol when compared to reference experiments with pure water addition.

Continuous investigation of the engine at the Viking plant has showed no significant build up of deposits neither on the piston top nor on the cylinder head. Likewise no corrosion or wear of the engine parts originating from the producer gas has been observed.

From oil analysis it was concluded that the expected oil life time of the Viking engine is 600-800 hours depending on the chlorine contents of the wood fuel.

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