Evaluation of a cyclone gasifier design
to be used for biomass fuelled gas turbines

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Abstract

This thesis is a result of experimental studies carried out as a part of the efforts made in Sweden and within the European Union to develop a technology that will make it technically and economically possible to use biomass as a gas turbine fuel. The process that has been studied is based on cyclone gasification of biomass powder and no further cleaning of the product gas from the gasifier.

The study covers four issues that are important for assessment of the possibilities to develop such a process to commercialisation:

1. The feeding of biomass to the gasifier
2. The efficiency of the gasification process
3. The product gas quality
4. The integration of the gas turbine and the gasifier.

The studies of the feeding system are presented in papers 1, 2 and 3. Screw feeders were used to control the fuel flow and ejectors driven by pressurised air or pressurised steam were used for injection of the powder into the cyclone. Two approaches for achieving feeding with small temporal variations were studied. One is based on use of a vibrator device in the feeding train, the other on use of a brush-like device positioned after the metering screws. Both systems were found to work reliably during the feeding tests and the subsequent gasification experiments.

The gasification tests aimed at determination of the quality of the gas produced from the cyclone gasifier. Stable operating ranges, generation of char residue, heating value of the product gas and amounts of contaminants in the product gas were studied. The results were compared with gas quality criteria provided by ABB Stal. Experiments were made at atmospheric pressure and elevated pressure.

The atmospheric gasification tests covered five different biomass powders. The results of these tests are shown in paper 4. Two of the fuels appeared as less suitable in the type of cyclone gasifier that was used.

The pressurised gasification tests included commercial Swedish wood powder fuel only. The results of the tests are shown in paper 5. For this fuel, stable gasification could be attained both at the atmospheric and elevated pressure. The gas quality fulfilled the criteria with exception for the amount of large particles (above 8μm). The implications of this will depend on the particle properties.

The experiences from attempts to operate the cyclone gasifier integrated with a gas turbine are presented in paper 6. Many difficulties where encountered during these tests. Stable operation of the gas turbine could be however achieved on a few occasions. The longest uninterrupted operation period was 34 minutes. Pressure transients appearing upon ignition in the combustion chamber of the gas turbine and design of the char discharge system at the cyclone bottom are the main unresolved problems.

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Vienna University of Technology is one of the partners in the project named "Cyclone gasification of pulverised biomass for operation of gas turbines in cogeneration plants". The project was financed partially by the European Commission in the framework of the Non Nuclear Energy Programme (JOULE III). A list of the partners is found in appendix 1. To them and all the other partners mentioned in appendix 1 I would like to express my thanks for the fruitful cooperation during the project period.

I want to express my thanks to my colleagues in the Department of Mechanical Engineering and especially to those in the Division of Energy Engineering for their support, encouragements and fruitfully discussions.

It is hard to find the right words to describe the role of professor Björn Kjellström in this work. He has not been only my supervisor but also a co-worker and supporter. He involved himself in many details and gave the impulses to think in new ways. He has been there when and where he was needed. To him I want to address my gratefulness.

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Contents

Appended papers

1. **Gabra M., Salman H. and Kjellström B.,** Development of sugar cane residue feeding system, Biomass and Bioenergy, Vol. 15, No. 2, pp 143-153, 1998
2. **Joppich A. and Salman H.**, Wood powder feeding, difficulties and solutions, Biomass and Bioenergy, Vol. 16, No 3, pp 191-198, 1999
3. **Salman H. and Kjellström B**., Pneumatic conveying of wood powder by using a steam-jet ejector Biomass and Bioenergy, Vol. 19, No 2, pp 103-117,2000
4. **Salman H., Pettersson E. and Kjellström B.,** Biomass powder gasification in a Cyclone Gasifier, Proceedings of 2001 Joint International Combustion Symposium, Sep. 2001 Kauai, Hawaii, USA
5. **Salman H., Pettersson E. and Kjellström B.,** Pressurised cyclone Gasification of Wood Powder, submitted to Biomass and Bioenergy for publication.
6. **Salman H. and Kjellström B**., Experiences from attempts to use a biomass fuelled cyclone gasifier for integrated operation with a small gas turbine, submitted to Biomass and Bioenergy for publication.

Introduction

The importance of biomass as fuel has increased during the last decades for two main reasons. The first one is the two oil crises and the second is the efforts to control the greenhouse effect. The international concerns about the greenhouse effect caused by the emissions of CO_2 increases. More and more measures are taken and agreements are signed. The last one is Kyoto Protocol. The protocol promises that the CO_2 emissions will be reduced to at least 5% below 1990 levels in the commitment period of 2008 to 2012.

There are several ways to reduce the CO_2-emissions and the use of biomass, as fuel is one of them. The world wide recoverable residue is estimated to be 31 exajoules per year or 10% of the global commercial energy use, see Babu, [1995]. Electrical power plants using direct combustion of biomass have efficiencies of 15-20% with electricity cost of 680-840 Skr/MWh. Babu's studies showed also that the cost of electricity can be reduced to 470-580 Skr/MWh by using combined cycle based on the gasification of the biomass to generate a gaseous fuel for the gas turbine. The efficiency will be 35-40%. The efficiencies given by Babu are lower than are given by others. The Swedish government Energy Commission gave figures of 30% for the conventional power plants and 40-50% for the combined cycle based on gasification, see SOU [1995]. However, the main point is that a combined cycle gives better thermal and economical results.

Gas turbines are generally designed to be run by clean fuels i.e. fuels with no ash or very low ash content. Biomass is a solid fuel with an ash content of 0,5-5% and that can cause several problems. Some of the solid residue of the solid fuel gasification in the form of particles is carried out by the product gas and may cause erosion. The ashes contain alkali metals that may cause deposition or corrosion problem. The deposition of ashes on the turbine blades causes a reduction in the performance of the turbine by reducing the flow area and changing the flow pattern. It is therefore the solid fuels cannot be directly used in firing a gas turbine and several ways have been suggested for the indirect use:

1) Hot air turbine, where the hot gas from biomass combustion are not passing through the turbine but used to heat pressurised air expanding in the turbine. The method was used in Germany at the end of the seventies but abandoned because of the high investment costs, see McDonald [1980].
2) Gasification of the biomass at atmospheric or elevated pressure and cleaning the gas before combustion to remove the ash harmful elements. The method allows higher inlet temperature to the turbine but the cost still high. Many studies have been published about this method. The IGCC plant in Värnamo, Sweden is one example of demonstration plant. Experiences have been reported by Ståhl and Neergaard [1998]
3) Gasification in a cyclone at elevated pressure with minimal gas cleaning in cyclones. The inlet temperature is limited to the melting temperature of the ashes and the efficiency of the process will be lower than that mentioned above but the investment cost will hopefully be lower. Fredriksson and Kallner [1993], Fredriksson [1999] and Gabra M [2000] have studied different aspects of this method. This thesis is a part of the continuing efforts to evaluate the method.

4) Liquefaction of the biomass by rapid pyrolysis and use of the pyrolysis oil as fuel after filtration, see López and Salvá [2000]

The gasification is a conversion by partial oxidation at elevated temperature of the biomass into a gas with a certain energy value and other products such as char and tar. The oxidant can be air, oxygen, steam or even self-oxidation as reported by Bain and Overend, [1996]. The gasification of the biomass can be achieved in many ways. Fixed bed reactors of the down-draft type are used mainly to generate fuel gas for the internal combustion engines. The maximum capacity is about 1 MW(fuel). Fixed bed reactors of the up-draft type generate a gas with more tar and are used mainly for generation of a fuel gas for combustion in a boiler or a furnace. Fluidised bed reactors are also used primarily for boilers and furnaces but there are a few examples of illustration for gas turbine operation.

The work presented in this thesis is a part of a project named "Cyclone gasification of pulverised biomass for operation of gas turbines in cogeneration plants". The project is partially financed by the European Commission as a part of the Non-Nuclear Energy Program (JOULE III) with the help of some Swedish and European companies (see appendix 1). The project aims to study the possibilities to use different types of cyclone gasifiers for generation of a fuel gas that can be used to run a gas turbine for co-generation plants. Three different cyclones have been tested at respectively Luleå University of Technology, Vienna University of Technology and Cardiff University. The project was planned to be finished within 30 months. Budget and time consideration characterized the big part of the work reported in this thesis.

The gasifier studied in this thesis is a conventional separation cyclone where the gasification of powdered biomass and the separation of the solid residue are done in the same reactor. The idea was presented by Fredriksson and Kjellström [1991] and since then tests have been carried out both at the Royal Institute of Technology (KTH) and Luleå University of Technology (LUT). The studies aim to:

- Feeding of the solid biomass to the pressurized cyclone gasifier.
- Establishing a stable gasification of the biomass
- Separation of ash particles that may cause erosion of the turbine.
- Avoiding carry-over of the volatile salts in the ash to the gas turbine where they may deposit and cause blockage or corrosion
- Running a gas turbine (Rover IS/60) by using the gas produced as fuel.

The studies of the feeding system are reported in papers 1-3. Paper 4 deals with the atmospheric gasification of different types of biomass where the main issue was to identify the fuels that can or cannot be gasified in the cyclone gasifier. The pressurised gasification of Swedish wood powder has been discussed in paper 5. The main issue was to define the conditions that give a gas suitable to run the gas turbine. Paper 6 presents the experiences obtained from attempts made to run a small gas turbine.

Deposition, corrosion and erosion in solid-fuel fired gas turbines

Overview

Gas turbines in general are designed to operate on very clean fuels. If the hot gas that is passed through the turbine carries too much and too large particles, deposits may build up on the surfaces inside the turbine and/or erosion damage may be caused. Condensing ash species may cause deposition and corrosion.

The effects of erosion and corrosion are obviously leading to reduction of the service lifetime. Deposition is leading to reduced performance in particular for single shaft turbines. These machines operate at a fixed speed and mass flow. Deposition in the turbine will lead to an increase of the pressure ratio and thereby a reduction in the margin to compressor surge. To avoid this, the inlet temperature to the turbine must be reduced which leads to reduced power output. In a two shaft turbine, the speed of the high pressure compressor will decrease and this will decrease the performance of the machine dramatically. Deposition may also lead to problems with rotor balance and in unfortunate cases to catastrophic failure.

For these reasons, the criteria as regards particulates in the gas entering the turbine and the presence in the gas of vaporised or liquid ash species that may deposit in the turbine are generally very strict. When biomass fuels are considered as fuels for gas turbines, the presence of potassium and sodium species in the gas are one of the major concerns.

De Souza [1999] gives 200 mg/m^3 at the inlet of the turbine as a maximum allowable particle load and claims that this is a standard in gas-turbine industry. Others require much lower particle loads and specify the maximum concentration for different particle size ranges. The criteria for particles in the gas, proposed by the Electric Power Research Institute (EPRI) are shown in table 1.

Table 1: EPPI ´s particle concentration recommendations (from Meadowcroft and Stringer [1987])

Particle diameter in μm	Max concentration in ppm
> 20	<0,1
10-20	<1
4-10	<10

As regards acceptable levels of potassium and sodium in the gas, De Souza Santos [1999] mentioned figures of alkali content that can be as low as 2 ppm while Luthra and Spacil [1982] estimated that the tolerated content in the gas is even lower, namely 20 ppb.

If the gas quality meets criteria like these, problems with deposition, erosion and corrosion may not appear. It is not obvious however that serious deposition, erosion or corrosion will appear if the particle load or the levels of potassium and sodium exceed the criteria. The design of the turbine and the operating temperatures will also have an influence. For this reason, it is important to examine the mechanisms behind the potential problems and the actual operating experiences from turbines that have been operated with fuels like coal and biomass.

Corrosion mechanisms

Corrosion appears to be relatively well understood. The corrosion is mainly a result of alkali salts such as sulphates and chlorides. The corrosion can be divided into two types, a high-temperature form (type I) with a peak at 850-900 °C and low-temperature form (type II) with a peak at 700-750 °C, see Meadowcroft and Stringer [1987]. Chlorides, which cause type I corrosion can react with sulphur at low temperature, and form type II corrosion. As the gas temperature decreases during the expansion in the turbine, it is expected that type II corrosion is more common. Meadowcroft and Stringer point out that the total alkali measured in the ashes carried by the gas is not necessarily relevant to the corrosion potential. The ashes may include stable species that are not corrosive.

Erosion and deposition

Erosion and deposition are partly counteracting phenomena. Particles in the gas may give either erosion or deposition or both. The properties and the size of the particles as well as the shape of the turbine blades and the material in the blades are important for the effects that will be caused. Deposition can also be caused by condensation of potassium and sodium species.

Erosion is a result of the presence of coarse particles in the gas entered the turbine. The hardness of the particles is probably also important. The restrictions on the maximum size of the particles and their content in the gas vary significantly depending on the machine used and the experience gathered by different gas turbine vendors. Meadowcroft and Stringer [1987] mention that experiments show that the erosion on the turbine blades could be caused by particles of size down to 3 μm. However, they also state that aerodynamic considerations have shown that particles with size less than 10 μm miss the target (blades) or at least change attack angle. That means less erosion than that shown in experiments where flat targets were used. Other researchers gave 10 μm or less as the limit of particle size in the gas at the inlet of the turbine (see for example Romeo [1999]).

Whether potassium and sodium species in the gas will lead to deposition problems or not depends on the species formed in the gasification and combustion reactions and also on the loading of particles in the gas and the properties of the particles. Dayton [2001] explains that deposition includes thermodynamics and chemical reactions in terms of gas composition, particle transport, gas and surface temperatures, fluid dynamics, and surface interactions and reactions. According to him, thermodynamics favours the release of alkali chlorides under most combustion conditions if chlorine is available in the gas. In the absence of chlorine, hydroxides are the next most likely alkali species to be released, and in the absence of hydrogen, alkali oxides form. The temperature is another factor that determines what species will form. At lower temperatures the alkali sulfates are stable. Deposit formation, therefore, is strongly dependent on the alkali species composition in the gas phase as well as the temperature of the gas and the surface on which the deposits form. Stevens [2001] pointed out that the low content of sulphur in biomass is enough for the formation of eutectic salts due to the reaction between KOH and KCl and sulphur and chlorine at a temperature of 700 °C or higher. However Blander [1997] showed that adding sulphur to aspen wood eliminates the fouling and corrosive carbonate rich molten salt.

Carbonates crystallize at a temperature of 800 °C while sulphate crystallizes at a temperature of 1000 °C. That should allow use of wood to fuel a gas turbine at a temperature of 900 °C or more after hot gas cleaning by cyclone or a filter.

That presence of ash particles can reduce the corrosion rate by gettering has been reported by Meadowcroft and Stringer [1987]. It is therefore likely that ash particles can also reduce deposition problems.

Experiences from use of coal or biomass as gas turbine fuel

Coal and biomass are likely to produce a gas with some particles and some content of potassium and sodium species. The latter may be in vapour form, as liquid droplets or included as solids in the particles. The level of these contaminants in the gas can be reduced, but not to zero, by gas cleaning.

Experiences from the coal fired PFBC plants built by ABB-Carbon have been documented in several papers by Jansson, see for example Jansson [1997]. A detailed report about Tidd PFBC demonstration plant was published in 1995 by Ohio Power Company. Both Jansson and other reported erosive wear in the blades of the gas turbine especially in the low-pressure turbine. The wear was reported to be a result of the plugging of the primary ash cyclone causing a carryover of coarse particles to the turbine. An interesting observation was made in the Escatron PFBC plant. The gas turbine there experienced less erosion wear than the other plants although the dust loading is higher through the machine due to the nature of the coal used there. The reason is believed to be the softer structure of the ashes there than those in Värtan and Tidd. ABB STAL´s experience from coal-fired gas turbines reported by Strand [1999] shows that the effect of the deposition on the performance of the turbine depends on the configuration of the machine. In the GT35P machine, the speed of the high speed rotor can be controlled by guide vanes. This can be utilised to avoid large deterioration of the performance as the result of deposits in the turbine.

Hamrick [1992] has reported results from operation of a gas turbine with three types of biomass fuel. The biomass was burned in a cyclone combustor followed by an additional cyclone for gas cleaning. The results show that the type of biomass, or perhaps rather the ash composition of the biomass, is very important for the occurrence of deposition. For tests done with Virginia pine saw dust and with an inlet temperature of 790 °C there was very little particle collection on the blades. Particles of 1.2 μm in diameter are collected on the blades when oak or poplar sawdust were used at a temperature above 705 °C. The levels of contaminants in the gas have not been reported.

Also Blander et al [1995] have described the problem of deposition in gas turbines that use biomass as fuel. They applied their equilibrium calculation model on a gravel-bed combustor developed at the University of Wisconsin-Madison for powering an Allison 250 gas turbine (300 kW output at 1000 °C and 4 bar). The inlet temperature was 750-900 °C in their 250-hour tests. They noticed that the average blockage due to deposits was 0.19% of the flow area per hour. The blades deposits were primarily CaO, MgO and K_2SO_4. Again the levels of contaminants in the gas have not been reported.

The Värnamo test plant in Sweden, using a pressurised fluidised bed gasifier followed by elaborate gas cleaning has been in operation for more than 8500 hour of gasification runs and about 3500 hours of operation as a fully integrated plant as per August 1999. The experiences from Värnamo pilot plant have been reported by Ståhl [1998,1999]. The turbine in Värnamo seemed to experience fewer problems than reported for the coal fired PFBC-plants. Engstrom [1998] reported that the gas contains less than 0.1 ppm in weight alkali salts and dust of less than 2 mg/Nm^3. The cooling of the gas and the high performance of the hot gas filter are some of the factors that gave such a result.

Gas Cleaning

The most common way to remove the alkali vapours is to cool the gases to a temperature below 650 °C and then clean the gas by cyclones and filters to remove the particles formed. The method causes a loss of sensible heat and reduces the efficiency of the system. Another method has been used where the gas temperature can be higher. The method is called alkali getters. Alkali getters use the principles of adsorption and chemisorption of the alkali vapours. Turn et al [2001] reported a reduction of potassium and sodium by 99 and 92% respectively from a product gas by using a bed of emathlite or activated bauxite. A third technology that is used by Westinghouse is Westinghouse advanced particle filter system. The system is described by Lippert et al [1996]. It consists of stacked arrays of filter elements supported from a common tubesheet structure. The arrays are formed by attaching individual candle elements to a common plenum section. The dirty gas filtered through the candles comprising the array is collected in the common plenum section and discharged through the clean side of the tubesheet structure. The arrays are cleaned from a single nozzle source. Several arrays can be used to form a filter. The filter has been tested in a Biomass Gasification Facility demonstration in Paia, Hawaii. The tests showed that the gas could be cleaned from a dust load of 2900 ppm to below detection limit after the filter when the cleaning cyclone was out of function. The alkali content was also below detection limit. The performance of the filter dropped as the cyclone was functioning. These results showed that the filter has better performance with larger particle size and therefore no cyclone is needed.

Gas quality criteria used in this study

It is obvious from the study of the earlier experiences that the quality requirements for the gas produced from the solid fuels can not be exactly defined. The criteria used by the different references that were studied are widely spread. It can also be concluded that the erosion, deposition and corrosion problems depend on the behaviour of the ashes of the biomass and the temperature levels in the turbine.

ABB STAL (now Alstom Power) was a partner in the cooperative European project in which this study is a part. Their interest was to investigate the possibilities to use a biomass fuelled cyclone gasifier to operate a GT35P gas turbine, i.e. the same type of gas turbine as used in the coal fired PFBC plants. For this reason gas quality criteria that were based on the experiences from the PFBC-plants were used for assessment of the gasifier performance. These criteria are given in table 2 below.

Table 2: Gas quality criteria used for assessment of cyclone gasifier performance

Heating value	> 2,5 MJ/kg gas
Total particle concentration in the product gas	< 3000 mg/kg gas
Concentration of particle >8µm	< 70 mg/kg gas
Alkali concentration	< 70 mg/kg gas

Also the melting temperature of ash species entering the turbine should be above the material temperature (about 850^{o}C).

The feeding system

The feeding system for supply of biomass powder into the cyclone gasifier must fulfil the following requirements:

1. The fuel-feeding rate required to give the desired inlet temperature to the turbine must be achieved.
2. Fluctuations of the fuel-feeding rate must be small (±10%), see Brown and van den Heuvel [1996].
3. The feeding of the fuel must be achieved with minimum flow of driving gas and carrier gas.
4. The fuel must enter the cyclone gasifier with high velocity.
5. The feeding system shall give a pressure gain exceeding the pressure losses in the cyclone.

Feeding of the biomass powder has been studied at Vienna University of Technology and Luleå University of Technology. The approaches taken are similar in the sense that ejectors are used to blow the powder into the cyclone gasifier. The designs used to achieve a relatively even flow of fuel and the driving medium selected for the ejectors are however different.

The objectives of the studies presented in this thesis were:

- To study different methods for achieving a powder flow with acceptably small variations.
- To study the effects of ejector geometry, driving medium and powder size distribution on the performance of the ejector.
- To compare the experimentally determined performances with predictions using models proposed in literature.

The fuel feeding systems studied at Luleå University of Technology (LTU) and Vienna University of Technology (ITTEA) include a fuel hopper from which powder is supplied by screw feeders. Screw feeders were chosen due to the linearity between feeding rate and the rotational speed. However, studies of screw feeder function showed that high variations in instantaneous feeding rate could occur. Such variations are not acceptable because steady and stable feeding of fuel is important for gas turbine applications. With a constant airflow through the compressor and the turbine the inlet temperature to the gas turbine is directly proportional to the fuel-feeding rate. If the fuel flow increases, the inlet temperature may become higher than the maximum design temperature and the turbine blades will be damaged. Moreover, according to specifications for turbines in the range of 4 to 8 MW electrical power, the changes of the gas heating value are limited to ±10% during operation at rated output. In case of turbines of lower output, somewhat higher deviations are acceptable, and vice versa for a higher power range, see Brown and van den Heuvel [1996].

To improve the uniformity of the feeding process two different methods have been used at LTU and ITTEA. While at LTU a brush-like device has been placed at the outlet of the screw conveyor, at ITTEA a separate vibrating conveyor has been positioned downstream of the screw. The method used by LTU made it possible to reduce the variations from ±100% to ±10% as shown in figure 1.

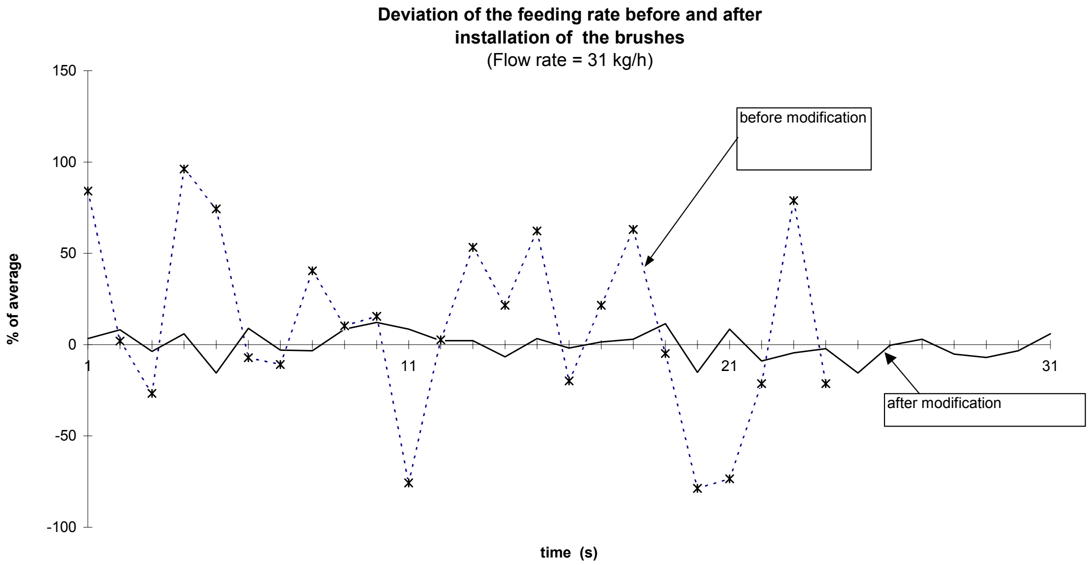

Figure 1: Feeding rate fluctuation with and without brushes

The tests done on the integrated facility with a gasifier and gas turbine and that are described in paper 6 showed that in the practical operation of the pressurised system, the variations in temperature increase over the combustion chamber were varied also within ±10%. This indicates that the fuel flow variations were kept within this range also in the pressurised operation. The inlet temperature reached about 900 °C. This temperature is higher than the highest inlet temperature to the turbine and also may cause high temperature corrosion; see Meadowcroft and Stringer [1987]. It is possible to avoid such effects by reducing the fuel rate (average inlet temperature). That will result in reduction of the output of the turbine. The other solution is to improve the feeding system to give lower variation in the feeding rate.

Paper 1 also deals with the feeding problem caused by the structure and the properties of certain biomass. Powders made by direct crushing of sugarcane and bagasse have low density and long fibres, which give cohesive characteristics and blockage of the feeding system. It was found possible to eliminate this problem by changing the shape of the slivers of the crushed bagasse/cane trash powder to render them more homogeneous. This was achieved by pelletising the crushed bagasse or cane trash before grinding the material to powder.

Paper 2 presents the method used at ITTEA for achieving a stable feeding rate. The performance is similar to that achieved at LTU. The tests presented in paper 2 showed also that there is optimal amplitude of the vibrator for every feeding rate, which gives minimum fluctuation in feeding rate. The optimal amplitude was found to be linearly proportional with loading as reported in paper 3.

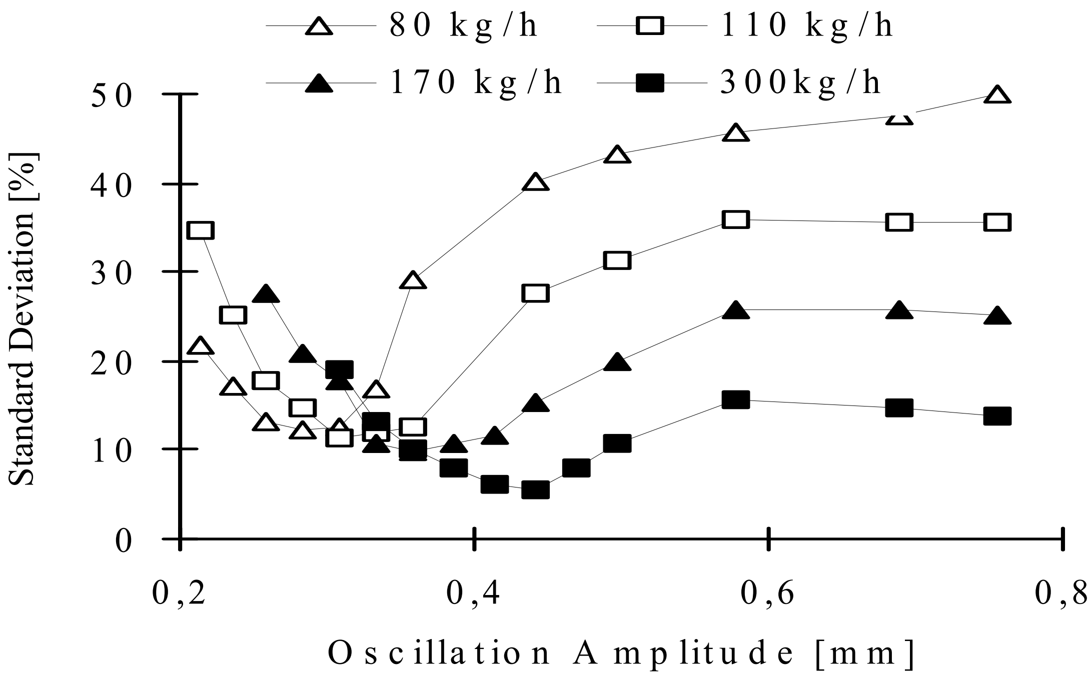

Figure 2: Standard deviations at different flow rates with screw feeder and vibrator

An important part of the feeding system is the ejectors. The ejectors can be used either for injection of the fuel powder only into the cyclone or for the injection of both fuel powder and the gasification-air. They should give the powder sufficient initial velocity to give high swirl because the particle separation performance of a cyclone depends strongly on the initial velocity of the particles. Paper 3 presents the results of experimental studies of the performance of jet ejectors for the feeding of powders made of biomass into the cyclone gasifier. A fuel to steam mass flow ratio (loading) of up to 25 has been achieved when Swedish wood powder with mainly fine particles was used and up at least 10 when sawdusts with bigger mean particle size were injected see figure 3. The figure shows the pressure gain and the loadings that can obtained by using an ejector with a convergent-divergent nozzle. The nozzle throat diameter used in these tests was 1,2 mm.

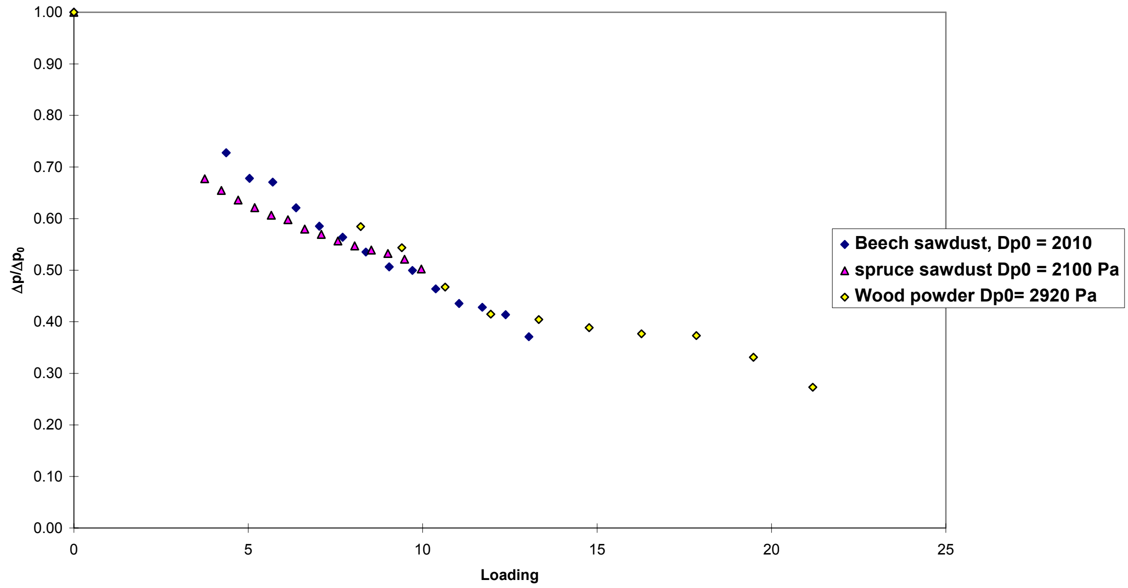

Figure 3: Pressure gain and the loading achieved with ejector using superheated steam

These tests were done without using any carrier air. This gives two benefits namely a reduced risk for powder explosions and that all the energy in the steam jet can be used to give a high particle velocity. The pressure gain during the atmospheric gasification tests could be measured and reported in paper 4. The measurements showed that the pressure drop from the down comers and the outlet of the cyclone was negative (1500-4500 Pa), which is mean that the pressure losses in the cyclone were more than compensated. The higher pressure gain in the gasification tests than that shown in figure 3 is a result of using nozzle with a throat diameter of 1,4-1,6 mm.

Paper 3 also includes a comparison between the experimental data for the pressure gain in the ejector and a theoretical model developed by Bohnet [1986]. The agreement is poor over the entire range of loading. After a study of the fundamental assumption in the model, two main reasons for its poor performance for the ejector geometry used in this study are observed:

- The possible pressure gain when a jet is injected into the ejector with zero flow of transported medium is overpredicted when the ratio between the diameters of the mixing pipe and the driving nozzle is large enough and the length of the mixing section is short enough to allow the driving jet to penetrate a significant part of the mixing section without reaching the walls.

- The acceleration of the particles is overpredicted. This is a consequence of neglecting the effect of particle drag on the driving gas velocity.

The modelling of the ejectors was studied later by Vienna University of Technology in the framework of the cooperative European project using CFD. The results of the model show a relative deviation of 1.1-17,6% in the relative pressure gain compared with the experimental findings. The highest deviation was just for the case studied by paper 3 where the secondary (carrier air) air flow is low. The convergence of the solution in these cases was the most difficult too. The model showed tendency of bridging even at low particle flow. Such tendency was not observed in the tests done at Luleå University at LTU.

Tests were done at Luleå University of Technology to examine the feeding system in the pressurised gasification facility. The experiments were focused on Swedish wood powder and done without gasification. The injection of the fuel was done by using air at 6 bar and 20 °C as driving medium. The airflow was 12 kg/h. It was found necessary to use a carrier gas of at least 0,4 kg/ kg fuel into the downcomers to achieve smooth feeding. A feeding rate of up to 52,5 kg/h for each ejector could be reached. With two ejectors the total feeding rate is 105 kg/h which is the highest rate needed by the gas turbine will be obtained. During the pressurised gasification tests only air has been used as driving medium. Pressurised gasification tests using steam as driving medium are planned. Some disturbance of the ejector feeding was observed during the start-up of the pressurised gasifier. These problems were discussed in paper 6. It was not possible to measure the pressure drop over the cyclone in these tests because of the clogging of the prop used for the pressure measurement inside the cyclone. Modification or replacing this prop needs the disassembly of the cyclone and that take long time.

It should be understood that continuous feeding of the fuel powder from atmospheric pressure to the pressurised fuel bin was not studied in this project. There are some commercial devices such as lockhopper system, rotary valves and piston feeders that might be used. Each of these has its advantages and disadvantages when they are used for pressurising and feeding biomass powder. More work is needed to decide which of these is the best choice.

The gasifier design

The cyclone gasifier is designed similar to a conventional separation cyclone. The design calculations were done by Fredriksson [1999]. Detailed descriptions of the calculation can be found in paper 5.

The experiments done by Fredriksson were done in atmospheric gasifier where the C.I. was between 3,8 and 5.3 MW/m^3.bar and it was the same for the atmospheric gasification tests reported in this thesis. In the pressurised gasifier the C.I. was between 2,6-4,1 MW/m^3.bar at pressure of 1.6-2,7 bar. These results show that it is possible to estimate the capacity of a cyclone gasifier at elevated pressure from a constant value for the combustion intensity.

Atmospheric cyclone gasification

The atmospheric gasification tests aimed to study the possibilities for stable gasification of different biomass and the quality of the gas produced. The tests aimed also to examine which biomass powder(s) are the most suitable for cyclone gasifier shaped like a conventional separation cyclone. Gasification experiments were carried out with five types of biomass powder in a cyclone. The fuels tested were commercial Swedish wood powder, sawdust from Austrian spruce, sawdust from Austrian beech, powder from willow coppice (Salix) and powder from canary grass. Steam was used for injection of the fuel and the gasification air into the cyclone. Tests were carried out where fuel and air were supplied through different inlets and through the same inlets. The fuel-feeding rate was varied between 27 and 40 kg/h corresponding to a thermal power of 140 to 200 kW. The results of these tests are described in paper 4.

Ranges of stable operation were established. It was found that stable gasification required a cyclone wall temperature above 700 °C. Product gas composition, residual char production, dust load in product gas and separation of potassium and sodium compounds were determined as functions of the air-to-fuel equivalence ratio. Some of these results are shown in figures 4-6 and compared with the gas quality criteria given by Alstom Power AB. .

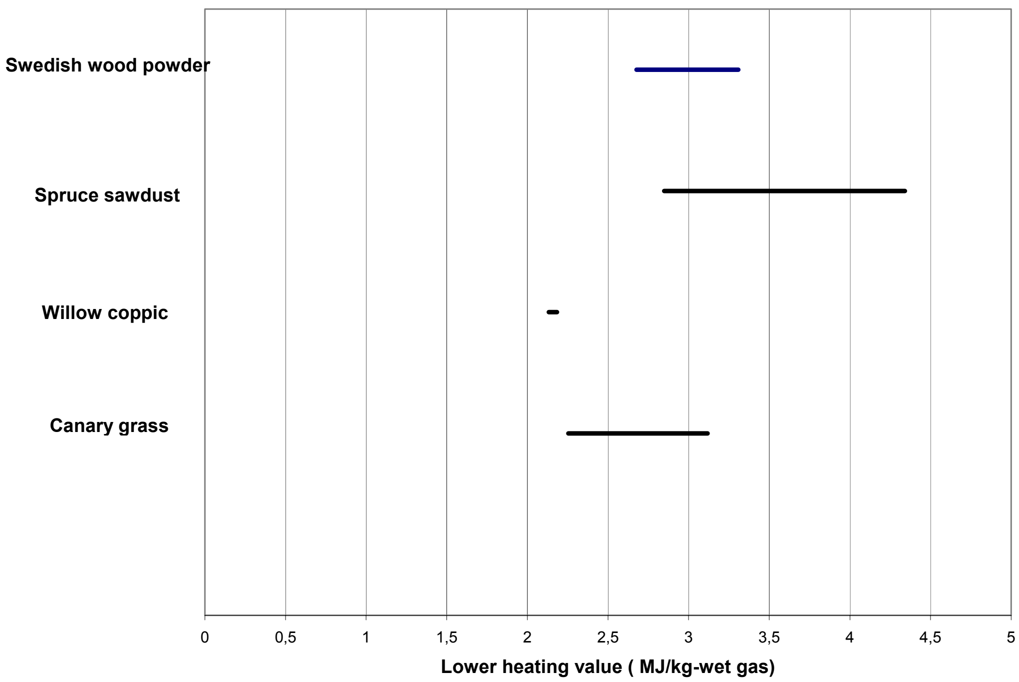

Figure 4: The ranges of lower heating value of the product gas from the atmospheric tests

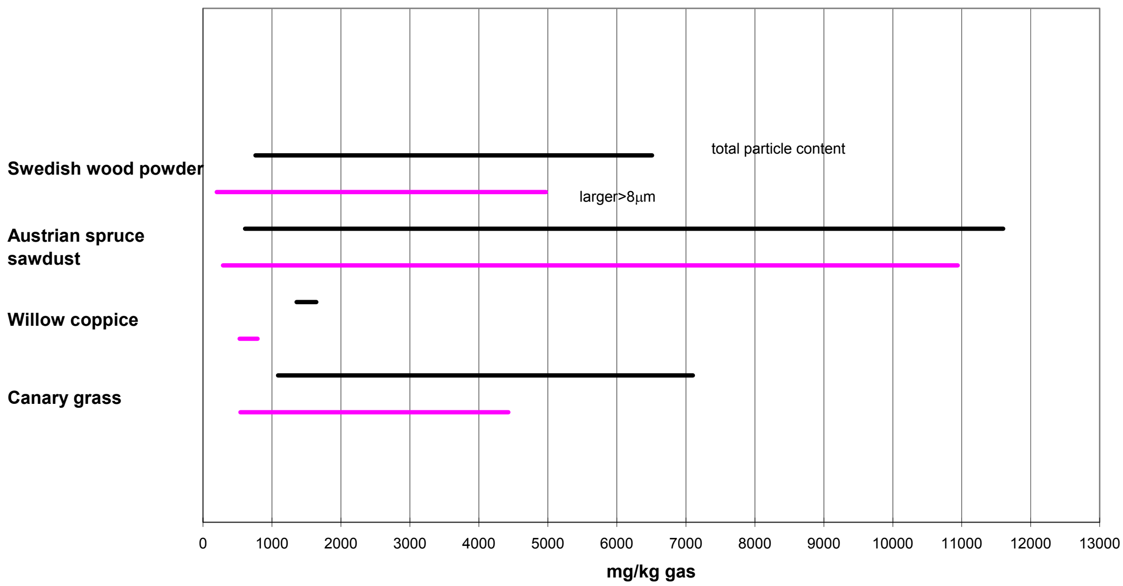

Figure 5: The ranges of the total particle- and coarse particle content in the product gas from the atmospheric tests

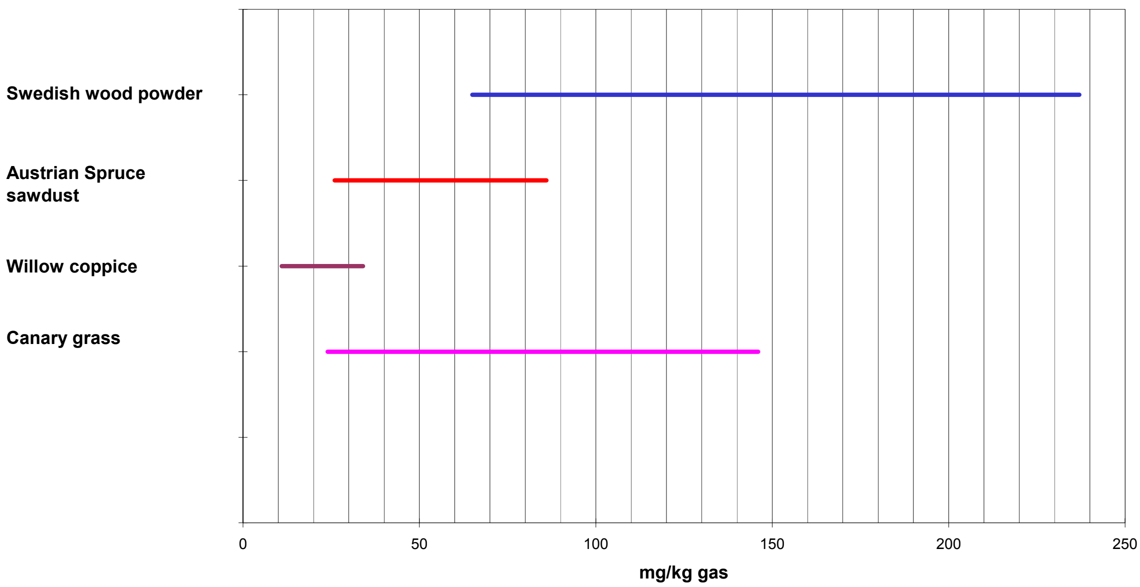

Figure 6: The ranges of the alkali content in the product gas from the atmospheric gasification.

Fredriksson [1999] and Gabra [2000] showed that the normalised K-content is slightly lower than that in the fuel and the normalised Na-content is almost the same as that in the fuel. The contents were normalised to the Ca-content since the Ca-species require higher temperatures for vaporisation. Fredriksson did his tests on Swedish wood powder and Gabra his on bagasse and cane trash. Both used the same gasifier that has been used in the tests reported in this thesis. Figure 7 shows the ratio of the normalised sodium and potassium in the separated char to that of the fuel. Table 3 shows results of a statistical analysis of the observations. The normalised K/Ca ratio is either significantly above 1,0 or not significantly different from 1,0 for all the tested fuel. This indicates that no potassium has been released from the separated char particles; in agree with Fredriksson and Gabra. The same applies for the normalised

Na/Ca ratio for Swedish wood powder. The Na/Ca ratios for spruce sawdust and canary grass are significantly below 1,0, indicates that some of Na has left the separated char particles for these fuels.

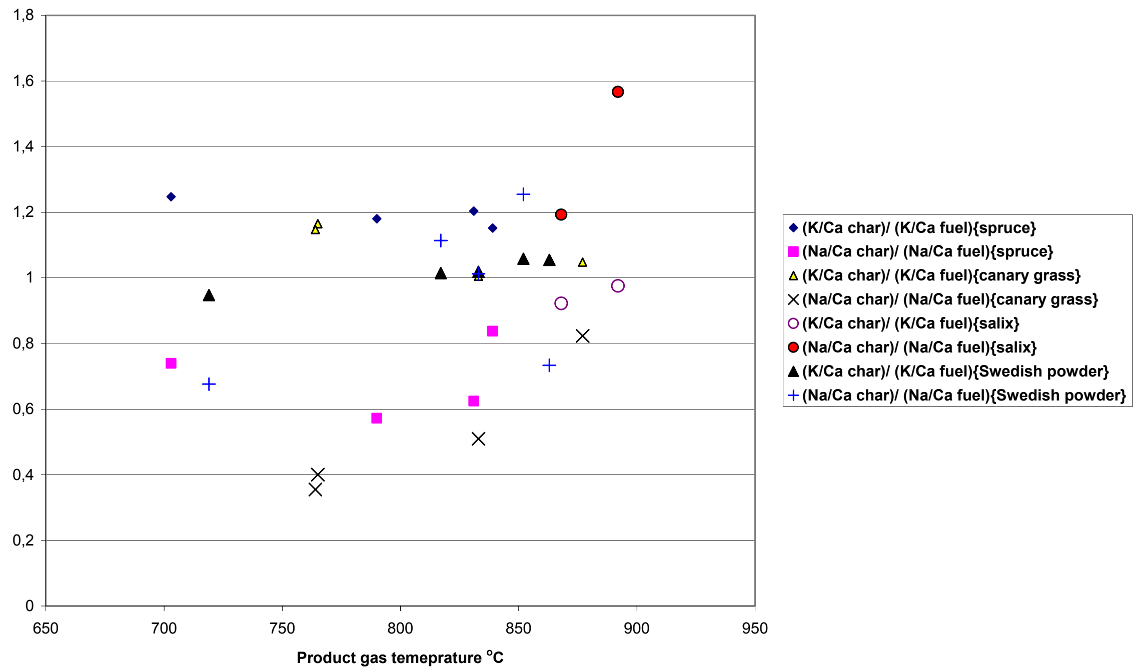

Figure 7: The ratio between the normalised sodium and potassium in separated char and in the fuels tested in the atmospheric gasification.

Table 3: Statistical analysis of normalised K/Ca and N/Ca ratios

Fuel	Swedish wood powder	Spruce sawdust	Canary grass	Willow coppice
		Potassium		
Average	1,02	1,20	1,09	0,95
Standard deviation	0,04	0,03	0,07	0,04
Null-hypothesis with t-test at 95% confidence level	1	More than 1	1	Only 2 points, not significant statistically
		Sodium		
Average	0,96	0,70	0,52	1,38
Standard deviation	0,24	0,10	0,18	0,26
Null-hypothesis with t-test at 95% confidence level	1	Less than 1	Less than 1	Only 2 points, not significant statistically

On basis of these experiments the following conclusions can be drawn:

- The Swedish wood powder and powder made of canary grass could be gasified under stable conditions when separate fuel and air inlets were used.

- The spruce sawdust could be gasified under stable conditions when air and fuel were injected together.
- The beech sawdust and powder from willow coppice could not be gasified under stable conditions. The beech wood has higher density than the other fuels and that gave shorter residence time. The long fibres of salix are suspected to have the same effect.
- All the tests with Swedish wood powder, spruce sawdust and canary grass gave acceptable heating values. Willow coppice powder gave too low heating value. During the experiments, the gas burned without problem however.
- Several test conditions gave acceptable levels for total particles for all the fuels. In particular canary grass gave a high particle load in the product gas. None of the test conditions gave acceptable levels for large particles. Some tests gave results a factor of 2-3 above the criteria, whereas others gave much higher values.
- Several test conditions gave acceptable levels for potassium and sodium.
- The K and Na species in the particles giving separated char will not be gasified under the conditions tested here.
- On the basis of the observation it was concluded that Swedish wood powder and Austrian sawdust are the most suitable fuel for this cyclone gasifier.

Pressurised gasification

Following the atmospheric gasification tests where five kinds of wood powders and sawdusts were tested a series of pressurised gasification tests were carried out with Swedish commercial wood powder as fuel. The system pressure during the tests was varied between 1.5 and 2.7 bar(a). The cyclone gasifier was similar in shape with that used in the atmospheric tests. Air was used for fuel injection. Fuel and gasification air were supplied together through two inlets.

The fuel rate was varied between 36-100 kg/h corresponding a thermal power of 180-500 kW. The composition of the product gas from the gasifier and the amount of the contaminations in the gas were determined. The main results of these tests are shown in figures 8-10.

The pressurised gasification tests showed that the gas has a heating value which is higher than that recommended. The heating value decreased with the feeding rate. This is because a higher equivalence ratio had to be used at low feeding rate in order to maintain stable gasification. As shown in figure 9, the total particle load in the product gas increases with the fuel rate. For feeding rates, above 60 kg/h, the particle load is higher than recommended (table 2). The observed level for large particles, above 8 µm, varies over a wide range. Most of the observations are in the range 55-366 mg/kg gas and it is believed that the two observations giving more than 800 mg/kg gas are erroneous.

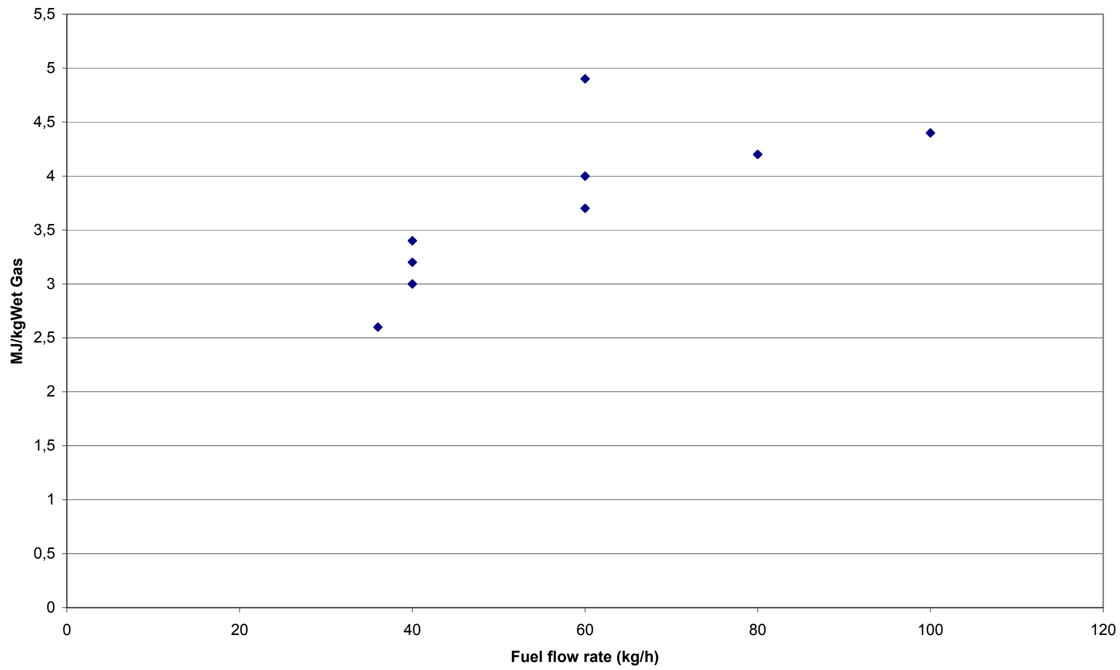

Figure 8: The lower heating value of the product gas of the pressurised gasification of Swedish wood powder.

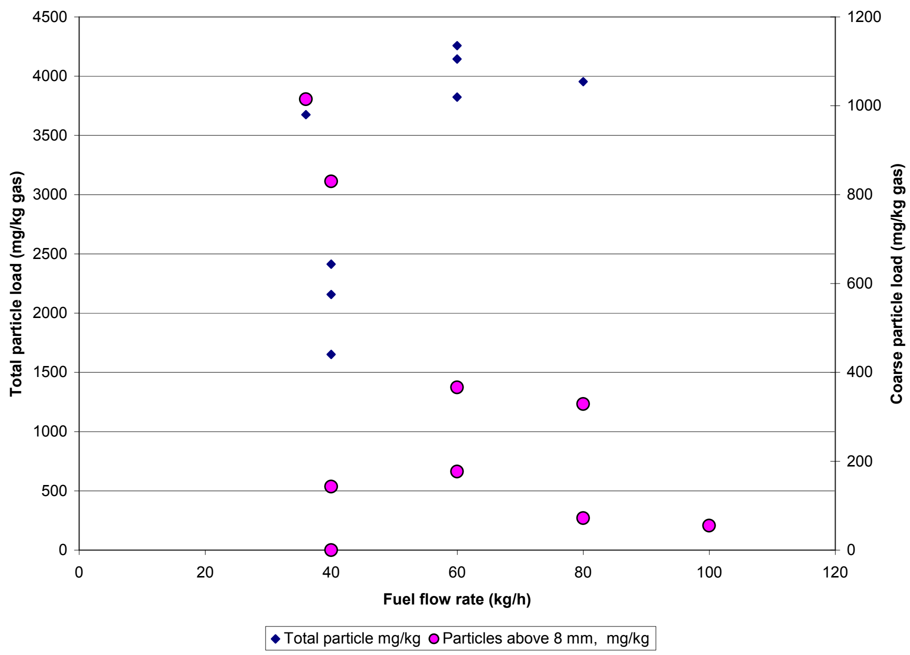

Figure 9: The total and coarse particle content in the product gas of the pressurised gasification of Swedish wood powder.

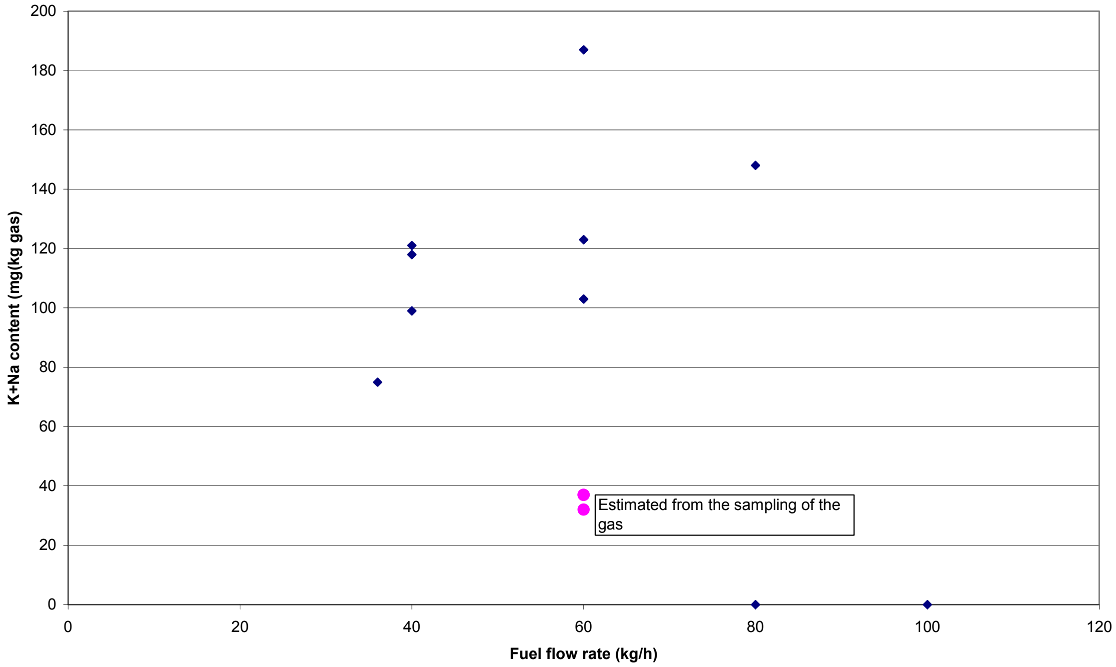

Figure 10: The range of the total alkali content in the product gas of the pressurised gasification of Swedish wood powder.

The content of the potassium and sodium in the product gas, calculated from the difference between the input of these elements with the fuel and the output with char separated in the cyclone are generally higher than the recommended levels, see figure 10. If the content is estimated from the sampling of the gas, the levels are acceptable as shown in figure 10. There are good reasons to believe that these results are more accurate, see papers 5 and 6.

In this context, the risk for release of gaseous potassium and sodium species from the char particles is of great interest. If this happens, the relative levels of potassium and sodium in the char would be lower than in the fuel. Fredriksson [1999] showed that for atmospheric gasification of the wood powder, the normalised K-content is slightly lower than that in the fuel and the normalised Na-content is almost the same as that in the fuel. The contents were normalised to the Ca-content since the Ca-species require higher temperatures for vaporisation. The same results were reported by Gabra [2000] for bagasse and cane trash that were gasified in the same gasifier at atmospheric pressure. The analysis of the char collected from the pressurised gasifier shows the same tendency, see figure 11. The mean values of the normalised ratios for K and Na, respectively, are 1,11 and 1,35 with standard deviations of 0,14 and 0,17. The normalised K/Ca ratio is not significantly different from 1,0 at the 95% confidence level. The normalised Na/Ca ratio is significantly above 1,0 in the same confidence ratio. The results confirm the previous conclusions that the alkali in the separated char were unaffected by the temperature and remain in the separated particles.

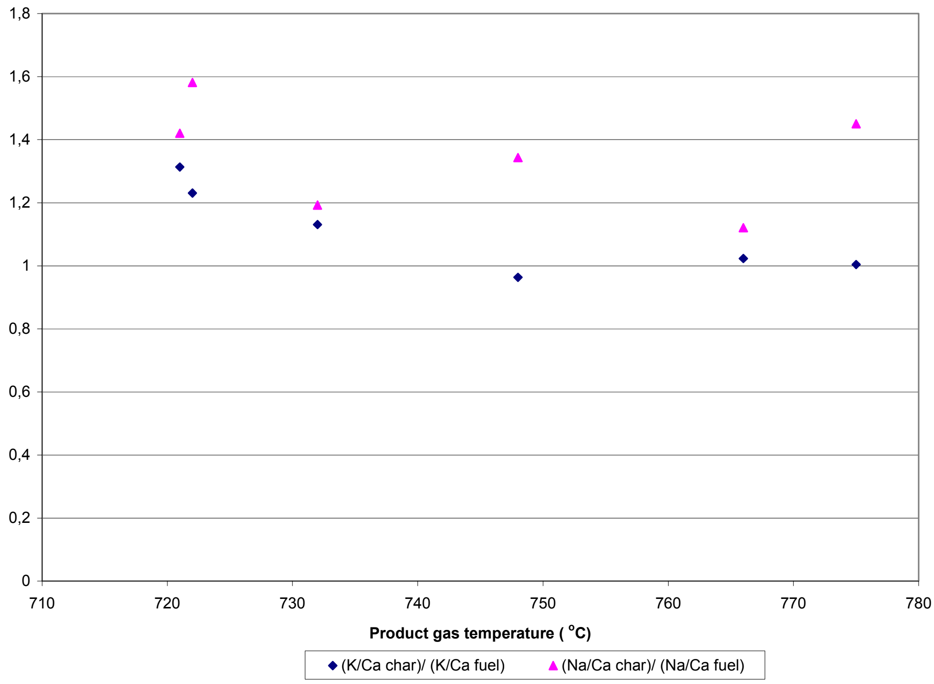

Figure 11. The ratio between the normalised sodium and potassium in separated char and in the fuel tested in the pressured gasification

Experiences from attempts to operate a small gas turbine with the product gas

Measurements of the quality of the product gas from the cyclone gasifier may give an indication of possible problems if the gas is used as gas turbine fuel. The criteria for gas quality that are shown in table 2 are however based on experiences with coal as fuel and do not cover all the possibly important gas quality aspects. The erosion effects will for instance depend on the hardness of the particles carried with the gas and not only on particle size.

Assessment of the possibilities to use the product gas as gas turbine fuel should therefore preferably be based on extended tests where the gas turbine in question is operated with this fuel. Tests at smaller scale, with a smaller gas turbine, may also give a better basis for assessment of the technology than just gas quality measurements. To make such tests possible, a test facility was built where the pressurised cyclone gasifier was connected to a Rover gas turbine with rated power output of 45 kW. The test facility and the experiences gained from the initial tests are described in paper 6.

The gas turbine was connected to the cyclone gasifier with a double-walled pipe. Part of the air from the Rover compressor flowed through the outer, annular channel in this double-walled pipe, to the pressure vessel surrounding the cyclone gasifier. The rest of the compressor air passed into the combustion chamber of the gas turbine. The product gas from the cyclone flowed through the inner tube of the double walled pipe to the gas turbine combustion chamber. The combustion chamber had been modified at the Royal Institute of Technology, see Duwig [2000] to allow combustion of the product gas from a biomass gasifier. It was found that some further modifications were necessary, in particular as regards the ignition of the gas. The studies made for this are described in paper 6.

The outgoing shaft of the Rover turbine was connected to a motor/generator with frequency control. By means of this, the rotor could be brought up to 34500 rpm during start-up. When the product gas ignited and the turbine power exceeded the power demand of the compressor, the motor acted as a generator and the frequency control kept the rotor speed at 46 000 rpm.

Over a period of about 6 months 59 attempts were made to achieve integrated operation of the gasifier and the gas turbine. Each attempt required a full days work. The time in between these tests was used for modifications, repairs and service of equipment and attempts to interpret the some times confusing observations that were made. All the pressurised gasification tests reported in paper 5 and discussed previously were in fact followed by an attempt to start the gas turbine.

Two of the difficulties have been mentioned earlier. Too rapid pressurisation of the system was found to result in clogging of the inlets to the fuel injectors for the cyclone. This was caused by a flow of fuel powder from the feeding bin that occurred even though the feeder screws were not operating. The other difficulty was the unreliable discharge of ash and char from the gasifier that was caused by the unreliable operation of the char discharge valves.

Failure to achieve stable ignition in the combustion chamber was preventing the integrated tests for several months. Part of the problem was that the original ignition system overheated when its was operated continuously. This was therefore replaced. The main problem was that the original position of the spark was not at point where the air-gas mixture is combustible. After studies of the radial air-gas distribution, a new position for the spark was found that resulted in more reliable ignition.

When finally ignition was achieved, it was found that the fuel feeding clogged shortly after ignition. Also on some occasions, a backfire into the fuel system occurred. This problem seems to be caused by the pressure wave that progresses faster up-stream the hot product gas channel to the cyclone than down-stream the colder air line when the temperature increases before the turbine. This would lead to a short period of reverse flow through the fuel injectors that could certainly cause the problems that were observed. In order to avoid this problem and to allow operation of the turbine with the hot burned product gas, a separate compressor was connected to the gasifier. This compressor supplied the gasification air to the cyclone and a corresponding airflow from the Rover compressor was bled from the system.

Totally seven tests have so far been made with more than a few seconds combustion in the combustion chamber. Four of these resulted in a net power output from the generator. The test conditions and the results are shown in table 4. The longest run lasted for 45 minutes. During this time electricity was generated for 34 minutes at an average power output of 58 kW. Table 4 also shows the predicted power output which agrees reasonably well with the measured value.

With the control system used, a net power output will not be achieved until the rotor speed arrives at 46 000 rpm. Until then, any excess power generated in the turbine is used to accelerate the rotor. Reaching steady state then requires 5 – 15 minutes. This explains why the same fuel feeding rate and not so much different gas temperature has given quite different turbine inlet temperatures and power outputs according to table 4.

During the tests where stable combustion in the combustion chamber was achieved, some variation of the gas turbine inlet temperature could be observed. The variation of the temperature increase across the combustion chamber is about ± 10%, or about the same as the variations in the fuel feeding rate observed during the calibration tests, see paper 1. This confirms that the fuel feeding variations are similar during practical operation as during the calibration tests. The obvious implication of these variations is that the average turbine inlet temperature must be reduced if the inlet temperature must be kept below a specified maximum level. This is undesirable since it also leads to reduced power output.

Table 4: Conditions and results from operation of the Rover turbine with burned product gas from the conventional cyclone gasifier

Test number	02-22	02-27	04-04	05-17	05-23	05-29	08-21
Fuel feed rate kg/h	70	70	60	100	100	100	100
Gasifier air/fuel equivalence ratio	0.28	0.27	0.31	0.27	0.28	0.26	0.26
Product gas flow (kg/s)	0,051	0,050	0,047	0,071	0,073	0,070	0,070
Turbine rotor speed rpm	40300	33260	35920	46000	46000	46000	46000
Gasifier outlet temperature ^oC	748	798	723	769	802	755	803
Turbine average inlet temperature ^oC	520	632	708	620	656	723	800
Burned gas flow (kg/s)	0,591	0,450	0,487	0,711	0,713	0,710	0,710
Average electrical power output, kW	0	0	0	29	33	46	58
Predicted electrical power output kW	-	-	-	32	35	44	53
Duration of test, minutes	0.5	3	1	3	7	8	34

Scientific contribution and remaining issues

Scientific contributions

The work behind this thesis has been focussed primarily on achieving operation of a small Rover gas turbine with product gas from a cyclone gasifier as fuel. The main objective was to collect operating experiences for assessment of the effects of contaminants in the product gas on the turbine. A number of issues related to fuel feeding, selection of fuels, system and component design had to be resolved before the turbine could actually be made to operate with the product gas as fuel. Many of these issues could have deserved more thorough studies. The project strategy that had to be applied because of time constraints was however to leave an issue as soon as sufficient information had been collected to proceed with the work towards the main goal. Severe practical difficulties were encountered. This also made it necessary to limit studies of interesting phenomena that were not judged as critical for making the turbine run on the product gas.

The information collected during the project is nevertheless considered by the author to be of some scientific value. The most important contributions are summarised below.

1. A feeding system for biomass powder has been developed that can supply fuel powder to a cyclone gasifier with variation less than 10% in the fuel flow. It has been shown that the flow variation caused by the variations in the feeding rate from screw feeders can be reduced either by using a brush-like device or a vibrating conveyer after the screws.

2. It has been demonstrated that it is possible to use a supersonic driving jet for injection of fuel powder with a jet ejector. It has been also shown that the ejectors can give a pressure gain that is higher than the pressure losses in the cyclone gasifier. Using ejector feeding may therefore eliminate the need of using a booster compressor.

3. The possibility of the use of superheated steam as driving medium instead of air as driving medium in the ejectors has been confirmed.

4. It has been shown that the theory presented by Bohnet [1986] can not be used generally for prediction of the performance of jet ejectors. The reasons for this have been explained.

5. Swedish commercial wood powder, canary grass powder and Austrian spruce sawdust have been identified as more suitable for gasification in the studied type of cyclone gasifier than Austrian beech sawdust and powder from short rotation forestry (Salix).

6. Experimental data for gas heating value, particles in the product gas and separation of potassium and sodium in a cyclone gasifier have been collected for gasification of Swedish commercial wood powder, canary grass powder and Austrian spruce sawdust at atmospheric pressure and for of Swedish commercial wood powder also at elevated pressure up to 1.9 bar.

7. The observations made in previous studies regarding gasification of potassium species from the char particles that are separated in the cyclone have been confirmed for canary grass and Austrian spruce sawdust at atmospheric pressure. For the Swedish commercial wood powder the observations were confirmed for both potassium and sodium at atmospheric and elevated pressure. This means that most of the potassium and sodium species in these particles is not gasified.

8. It has been confirmed by experiments that the modifications of the original Rover combustion chamber suggested by Duwig [2000], after adjustment of the position of the ignition spark, are adequate for combustion of the product gas from the cyclone gasifier.

9. It has been shown that the gate valves are not suitable to be used under the conditions prevailing at the cyclone bottom outlet.

10. The possibility of running a gas turbine Rover IS/60 by the gas produced in the pressurised cyclone gasifier has be demonstrated. It has also been shown that the power output is close to what can be predicted from performance data established with diesel oil as fuel.

Remaining issues

It is obvious that the main remaining issue is the effects of using the product gas as fuel for extended operation of the Rover gas turbine. The total particle load exceeds the recommendations and so does the load of larger particles. The particle load is highest at the high fuel feeding rate that is needed to reach the rated power output. There is some uncertainty about the potassium and sodium in the product gas, but it appears that most probably the levels are lower than the recommended 70 mg/kg gas. Operation of the turbine for at least 200 hours will be needed to clarify this issue. Additional gas cleaning, for instance by installation of a cyclone between the gasifier and the turbine, is a measure that can be considered if it turns out that the high particle load leads to problems. Improvement of the gasifier cyclone would be another possibility.

Other high priority issues are the char removal from the cyclone gasifier and the effects of the pressure transient that occurs when the product gas ignites in the combustion chamber. A possible temporary solution to the problems caused by unreliable function of the valves used for char removal could be removal of the valves and installation of a pressurised char collection tank below the gasifier. At least two possibilities for elimination of the problems caused by start-up pressure transients can be suggested. Both require considerable modifications of the hardware in the test facility. One possibility would be to install a starter burner in the combustion chamber and operate the turbine with combustion in the combustion chamber before wood fuel is injected into the gasifier. Another possibility would be to connect the combustion chamber directly to the gasifier.

Continuous operation of a biomass fuelled gas turbine with a pressurised gasifier obviously requires that the fuel can be brought from atmospheric pressure to the pressurised fuel bin. Pressurising of the fuel powder is an issue that has not been studied in this part of the European project. A state of the art review was however carried out by one of the partners in the project.

Reduction of the fluctuations in turbine inlet temperature is certainly desirable. The tests done with operation of the Rover turbine showed that the inlet temperature to the turbine could be up to 900°C at full load when the average inlet temperature was 800°C. Temperatures higher than 900 C may cause high temperature corrosion. Reduction of the average inlet temperature is of course a possible measure to reduce the peak temperature but this leads to a reduction of the power output. Most probably the temperature fluctuations are caused by variations in the fuel feeding rate but variations in char discharge may also contribute.

Use of steam as driving gas for the fuel injectors was never seriously tried in the pressurised gasification tests. The reason was some initial difficulties, when this was tried, in combination with time constraints on the project. The difficulties were probably caused by low steam temperature before the driving gas nozzles. Steam is an attractive driving gas for several reasons and pressurised gasification tests with this driving gas should therefore be made.

Issues of lower priority that might be studied if the issues mentioned above can be resolved in a satisfactory way, are:

- The performance of the pressurised gasifier for other fuels;
- Scaling of the gasifier to larger capacities;
- Optimisation of the fuel injectors, in particular with respect to minimisation of the need for carrier gas.

The crucial question is whether the separation of potassium and sodium that can be achieved by the cyclone gasifier makes any difference as regards problems in the turbine, in comparison with direct combustion of the biomass fuel where most of the potassium and sodium will pass through the turbine. Extended tests at realistic turbine inlet temperatures with direct combustion of different types of biomass are therefore at least as important as the extended tests with gasifier operation.

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Appendix 1

Partners

The partners participate in the project Cyclone Gasification of Pulverised Biomass for Operation of Gas Turbine in Cogeneration Plants.

1) Luleå University of Technology (LUT)
2) Vienna University of Technology (TUWien)
3) University of Wales, College of Cardiff (UMC)
4) Tampere University of Technology (TUT)
5) Kungliga Tekniska Högskolan (KTH)
6) Vattenfall AB, Thermal Power (VV)
7) Alstom Power AB (earlier ABB Stal AB)
8) Babcock Borsig Power, Austrian Energy BBP
9) James Engineering (Turbines) Ltd (J.E.T. Ltd)
10) Energiteknisk Centrum I Piteå (ETC)

Financing

1) European Commission
2) Swedish National Energy Administration
3) Vattenfall AB, Thermal Power (VV)
4) Alstom Power AB (earlier ABB Stal AB)
5) JET
6) BBP