Final report

ForskEL project no. 2009-10267

LTCFB demonstration plant

Phase 1

Design project

September 2010

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1. Conclusion

The objective of this project was to establish a firm basis for making a decision whether to build a demonstration plant based on the LT-CFB gasification technology or not.

Based on the results from this project, it was decided to build the demonstration plant and funding was secured from within DONG Energy, from the ForskEL and ForskVE programmes and from partners in the project.

The demonstration plant will be 6MWth and will be commissioned using straw pellets. Later on, other fuels will be tested. The demonstration plant will be placed at Asnæs Power Station near Kalundborg and the gas will be cofired with coal in the existing Asnæs Power Station, unit 2.

This design project was called “LT-CFB demonstration plant - Phase 1” and the following construction project was considered “Phase 2”. The name of the construction project was later changed to “B4C – Biomass for Conversion”. The construction project includes establishment and operation of the demonstration plant and will be divided into three phases:

Phase 1 – Upscaling:
The gasifier and auxiliary equipment is built and tested while flaring the gas

Phase 2 – Integration:
Modifications are made so that the gas can be utilised in Asnæs Power Station, unit 2 and coal is substituted

Phase 3 – Demonstration:
Long-term testing is performed with a fully automated gasifier.

Within a period of four (4) years, the demonstration plant will be constructed and tested. The results will make it possible to further scale up the low-temperature gasifier to a commercially attractable size and give valuable information about long-term operation, operational economy and capital investment.

This design project has made it feasible to proceed with construction of an LT-CFB demonstration plant. This is a vital and necessary stepping stone for the process to get a commercial break through.

With the current focus on bioenergy worldwide, it is foreseen that the LT-CFB technology has a promising future for eco-friendly power production based on low-value biomass and waste products.

2. Background

The LT-CFB process was invented in 1997. A first national patent application was filed by DFBT, and the concept was suggested for its primarily intended purpose of indirect co-firing of straw and similar difficult types of biomass and residue products at large-scale fossil-fired power plants.

A first proof and optimisation of the concept were achieved by building and testing a small 50kW$_{th}$ test plant at the Danish Technical University (DTU). This early work was supported by the Danish Energy Agency.

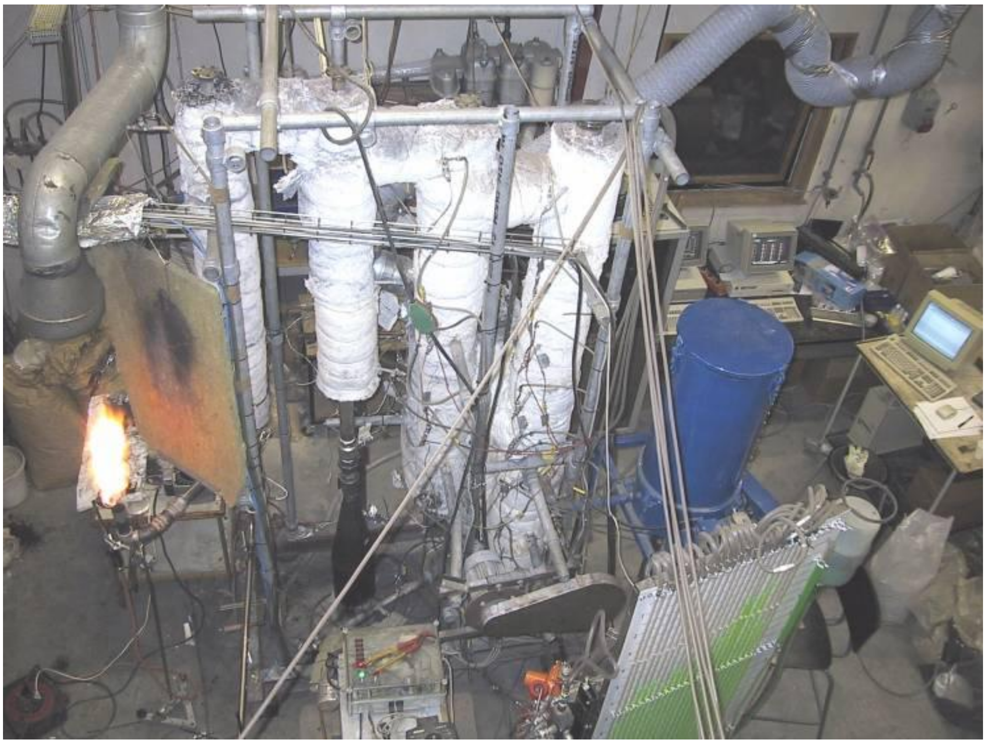

Figure 1: 50kW test plant at DTU

Further, 50kW$_{th}$ tests and optimisation work were performed within a first ForskEl project (Eltra PSO no. 3106) which also comprised the design, erection and first start-up of a 500kW$_{th}$ plant also located at DTU. The project also comprised a comparison of the intended type of indirect co-firing with the alternatives of direct (mix) co-firing and co-firing in separate biomass boilers at the level of around 80MW$_{th}$.

During the consecutive ForskEl project (PSO no. 4833), concluded early 2007, the 500kW$_{th}$ plant was tested using four different types of fuel, and several plant improvements were made. Moreover, a simple design study of a 6MW$_{th}$ plant was conducted.

Figure 2: 500kW test plant at DTU

The latest ForskEl-2007 project (PSO no. 7504) aimed at replacing the former 50kW$_{th}$ plant with a new, easier to move and more automated 100kW$_{th}$ plant which also reflects the experience gained from the 500kW$_{th}$ plant. Being easier to move allows for testing new fuels available and allowed to handle at other locations such as at the premises of potential hosts for scaled-up demonstration or commercial plants. The project also comprises an evaluation of the market potential in Denmark as well as the initial development of a business plan for an intended new 'LT-CFB company'.

The new 100kW$_{th}$ plant is also used for tests at Risø-DTU with the aim of evaluating various options for further cleaning the gas in order to make it usable for more demanding applications. These ongoing activities are funded by PSO-Eranet project no. 10111.

Figure 3: 100kW test plant at DTU

Great benefits have been achieved through coordination with a number of education projects and also a PhD project at DTU.

2.1 Relevance

The LT-CFB technology makes is possible to utilise various biomass and waste fractions that otherwise cannot efficiently be utilised within the energy sector.

DONG Energy has decided to transform into a low-carbon future in only one generation. With respect to CO_2 emissions, DONG Energy is presently based on 85% fossil fuels, but the vision is to reduce that to only 15% in one generation. This vision will be referred to as *85/15 in one generation.*

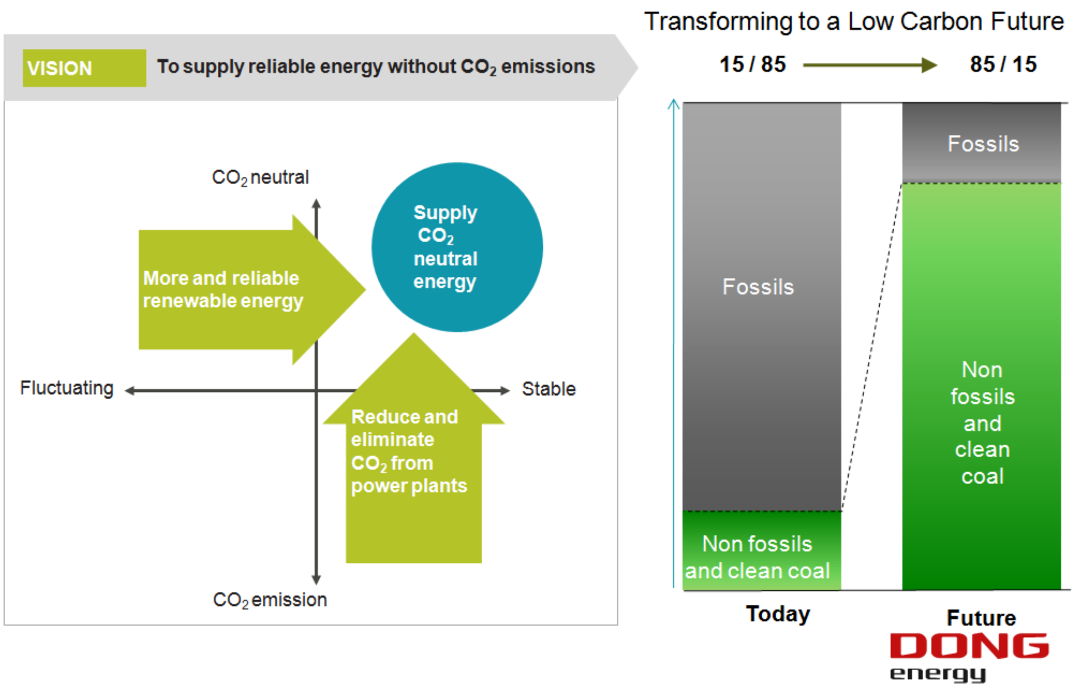

Figure 4: DONG Energy's 85/15 vision

As biomass and waste are the only storable CO_2-neutral energy sources we have in Denmark, they will play a huge role in order to balance the fluctuations created from especially the wind, wave and solar energy. Then the question is: How can we replace coal with biomass in existing assets optimised for coal? The quick answer is to import wood pellets, but wood pellets are expensive and limited, and in this respect they do not differ very much from crude oil.

We need to develop a technology which can utilise all kinds of local biomass and waste fractions. The LT-CFB technology has this feature, and in the short run, it can be used for co-firing coal units with biomass and waste, but in the long run, the technology has the potential to also deliver a clean gas to small local gas-fired units.

2.2 Status for the development of the LT-CFB process

The process involving testing and optimisation of the 50kW$_{th}$ plant and the 500kW$_{th}$ plant has made the LT-CFB gasifier ready for further upscaling and demonstration. The practical experience has been substantiated by thorough theoretical work. The upscaling by a factor of 10 was very successful, and further upscaling by at least a factor 10 from the 500kW$_{th}$ plant is considered as feasible without major technical problems.

Earlier the primary LT-CFB R&D partners have been DFBT, Risø-DTU, FORCE Technology, Anhydro and DONG Energy (formerly DFBT, DTU, dk-Teknik, RicaTek Engineering and Elsam Engineering), and a broad network to other companies and institutions (eg within the farming sector) has also provided valuable contributions.

DONG Energy chose not to participate in the ongoing ForskEl 2007 project but took a leading role in this ForskEL 2008 design project.

2.3 LT-CFB process description

A primary objective of the LT-CFB (low-temperature circulating fluidised bed) gasification process is to make it possible to use bioresources with a high ash content to substitute fossil fuels at large-scale power plants, and to produce electricity and heat with a high efficiency. When adding a large share of biomass with a high ash content directly to a high-efficiency boiler, considerable fouling and corrosion are likely to take place, and the mixed fly ash and slag can typically not be used for cement and concrete production. The low and well-controlled temperature in the LT-CFB process makes it possible to keep the problematic ash components in solid states and to separate them from the combustible gas. The cleaned gas can then be led to the furnace of a high-efficiency boiler plant, and in this way problems regarding fouling, corrosion and ash usage can be avoided.

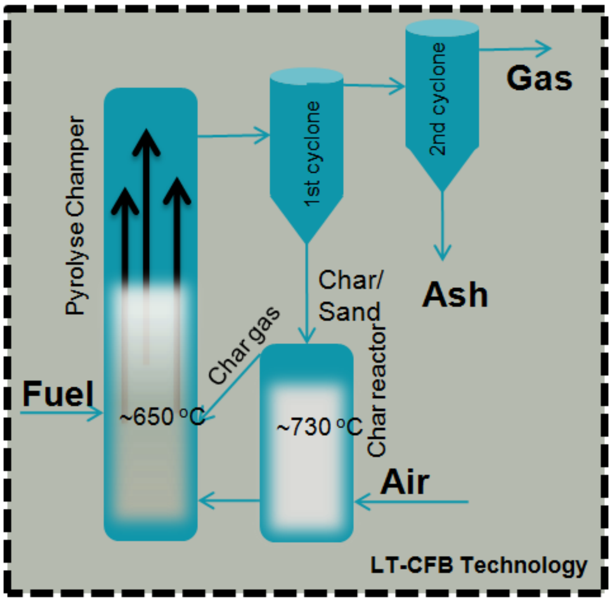

Figure 5: LT-CFB flow diagram

The process has been more thoroughly described in earlier publications.

3. Objectives

The purpose of this project was to design a complete demonstration plant based on the Low Temperature Circulating Fluidised Bed (LT-CFB) gasification technology.

The following preconditions were decided:

- The demonstration plant should be an approximately 10 times scaled-up version of the 500kWth LT-CFB test plant placed at DTU
- The product gas from the plant must be utilised in an existing DONG Energy owned power plant boiler
- The demonstration plant should be designed so that it is able to gasify different types of difficult biomass with a high alkali and ash content, eg straw, manure and biogas residue.

Furthermore, a detailed budget and time schedule for establishment of the demonstration plant should be made.

Based on the results from this design project, an application for funding of the demonstration plant should be made and handed in to Energinet.dk in September 2009.

4. Project organisation

The three (3) partners in the project have been working closely together and the knowledge of each partner has been utilised to deliver a good end product.

DFBT has delivered key knowledge of the gasification process and the design of the reactors and also data for expected analysis of the product gas, flows, temperatures, pressures, etc.

Risø-DTU has made it possible to perform tests with the 100kW plant and has also contributed to the safety analysis with key knowledge of operational experience with gasifiers.

DONG Energy has coordinated the project and designed all auxiliary equipment, handled approvals, etc. Experienced people from different sections within DONG Energy have contributed to find the best technical solutions for the demonstration plant within each subtask.

Consultants have been hired in to help with specific minor tasks.

5. Results

The design project was divided into subtasks as described in the following.

As described in chapter 8: “Business Strategy” DONG Energy has bought the rights for the technology and intends to develop and invest further in order to bring the technology to a commercial level. In order to protect the investment and the technology, the results from the design project will not be described in details in this report.

5.1 Fuel

One of the first things that were investigated in the project was which types of fuel the demonstration plant should be designed for. The LT-CFB process is very fuel flexible and is able to gasify a wide range of different fuels. The necessary equipment for transport, storage, handling, preparing and feeding of different fuels can, however, be quite different and focus on a few types of fuel is needed in order to keep the cost of the demonstration plant at a minimum.

Manure fibres and biogas residue are a vast, primarily unused bioresource for energy purposes. Several earlier tests with the LT-CFB test plants at DTU have shown that the process is very suitable for utilising both the energy content in the fuel for efficient electricity production and the nutrients for making a fertilizer suitable for farmlands. In order to be able to gasify manure fibres or biogas residue, the raw material needs to be dewatered and thermally dried. For transport and storage purposes the best solution is to dry the material to reach a water content below 15%. Handling is also easier if it is pelletised.

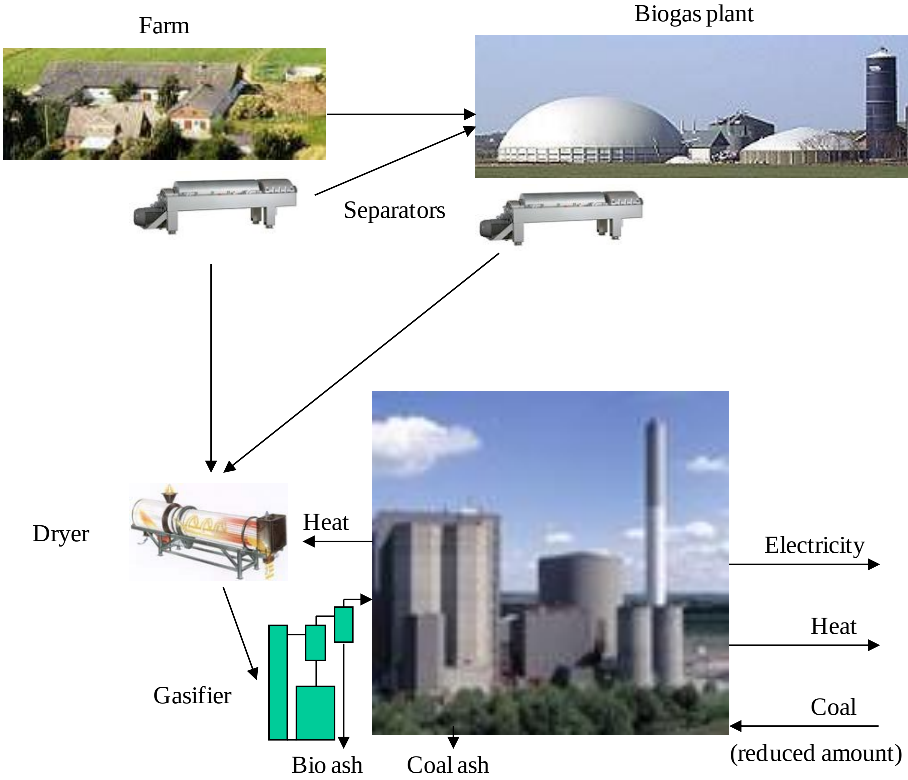

Figure 6: Example of flow sheet for gasification of manure fibres or biogas residue

A complete logistic chain was considered, sketched and economically assessed for manure fibres and biogas residue. Due to the limited amount of operational hours anticipated for the demonstration plant during especially the first couple of years, the investment was considered relatively too large. Also only very limited references could be found for dryers and manure fibres, so also the drying step would be a development project itself. This was therefore excluded from the project.

There is still unused straw in Denmark and vast amounts in our neighbouring countries. The LT-CFB process has also proved to be an efficient tool to remove alkaline and ash from the straw and produce a gas suitable for eg coal-fired boilers. Studstrup Power Station has been successfully direct co-fired with straw and coal for a several years but this solution has some limitations. Only 10-15% of straw related to coal can be co-fired for the ash to be used for concrete production and the steam parameters must be kept lower than state-of-the-art. Gasification of straw with the LT-CFB process is therefore considered a good technical solution also in the future.

It was concluded that the best solution for the demonstration plant would be to go for a simple solution with regard to fuel handling. The purpose of the demonstration project must be to focus on demonstration of the gasification process and use of the gas in a power plant boiler and not to test fuel preparation and handling systems.

The commissioning and first tests of the demonstration plant will therefore be done using straw pellets. The former three test plants at DTU have also been started up using straw pellets, so results can therefore be directly compared. The equipment for fuel handling and storage will be kept simple and only equipped with a minimum of automation.

Later, other fuels like manure fibres and biogas residue are anticipated to be used but they must be dewatered and dried prior to delivery to the gasifier site. It is anticipated that the demonstration plant will later on be used for testing of a wide range of different biofuels.

The fuel amount for the gasifier is 1.3-2.5 t/h depending on the heating value of the fuel. A very small storage of pellets on site is anticipated. A disc mill will be used to grind the pellets and the feeding system will be based on rotary valves and screw feeders.

5.2 Ash utilisation

All tests performed at DTU with the former three test plants have shown that the ash from the gasifier does not contain too high concentrations of any substances to be used as farmland fertilizer. This also regardless of the fuel used (straw, manure, biogas residue). This relates to PAHs, heavy metals and dioxin. The ash can therefore be distributed directly to farmlands.

The analysis of the ash has indicated that the nutrients in the ash have a relatively high availability to plants but more thorough investigations are needed. It is also a possibility to upgrade the ash and use it for production of commercial fertilizer products.

When the first ash has been produced from the demonstration plant, it will be analysed and conclusions will be made for how to utilise it in the best way.

The ash is extracted from the process via cooled ash screws and led to big bags for easy handling and storage for the first tests. Later, a container solution is anticipated.

5.3 Size of the demonstration plant

The first test plant at DTU was designed as a 50kW plant but actually proved to be most suited for 40-45kW depending on the fuel. The plant was scaled up using a factor of 12 to a 500kW plant. This upscaling did not introduce any problems. For the demonstration plant it was therefore decided to scale up with a factor of 12 again to a 6MW plant.
A brief design study performed in 2006 (PSO project no. 4833) had also been made on a 6 MW plant and some results from this could be reused and built upon.

5.4 Location of the demonstration plant

The main purpose of the project was to scale up the process and to demonstrate the use of the gas for electricity production in an existing power plant boiler. A screening was done of all of DONG Energy's power plant boilers and three locations were more thoroughly compared.

The best location for the demonstration plant was found to be Asnæs Power Station with co-firing of the gas at Asnæs Power Station, unit 2 (ASV2), primarily for the following three reasons:

1. ASV2 is coal-fired and the gas will substitute coal resulting in a CO_2 reduction and operational co-firing experience with the most common type of fuel used in power plant boilers
2. ASV2 is DONG Energy's smallest coal-fired unit (147MWe) and it is able to operate at a very low minimum load (90MWth). This boiler therefore offers the best possibility to be able to see the influence of the gasifier on the combustion and ash products. The obtained results can therefore easier be correlated to future full-scale gasifiers of 50-100MWth co-firing into larger boilers
3. The Asnæs site is fairly large and offers enough space for the gasifier and auxiliary equipment and also ample space for future rebuilds and additions to the demonstration plant.

The site for the gasifier at Asnæs Power Station is indicated below with the red square in the south eastern corner of the coal yard. The gas is utilised in Asnæs Power Station, unit 2. The boiler and turbine is marked with '2'.

Figure 7: Asnæs site and location of gasifier

5.5 Approvals from authorities

An early preliminary talk with the environmental authorities indicated that a full EIA (environmental impact assessement) application was not needed for this type and size of plant.
In October 2009, an environmental application was submitted to Miljøcenter Roskilde and in April 2010, a signed approval was received.

An application for a building permit was submitted in January 2010 and approval given in April 2010.

5.6 100kW tests

This project supported 100kW test number 8 performed at DTU in January 2010. The results from the tests are described in a separate report (appendix 2).

Main results from the test were:

- Stable operation was obtained during the 50 hour test even though a high content of potassium (8%) was measured in the bedmaterial at the end of the test.
- No fresh sand or additives were used during the test
- The char loss was as low as 2,5 energy% of added heating value in the straw

These results strengthen the earlier operating experience with the LT-CFB process. Especially the high potassium content in the bed material indicate that the needed amount of fresh sand will be very low also during long term operation.

The results from this 100 kW test will be compared with the first results with the 6 MW demonstration plant.

5.7 Safety analysis

It is good design practise to perform a safety analysis during the design phase of a new piece of equipment. In this case new technology is used with only a few references and several new technical solutions are introduced throughout the plant.

A lot of effort was therefore put into a safety analysis (HAZOP) of the gasifier and auxiliary equipment. This was done with assistance from COWI A/S who had earlier performed safety analyses for other gasification plants.

The safety analysis gave many inputs to the design of the gasifier and the necessary auxiliary equipment and to the PI diagrams.

5.8 Design of gasifier

The earlier 6MW design project (PSO no. 4833) was used as a basis for the design of the different reactors for the gasifier. The dimensions were recalculated and assumptions modified with the new knowledge gained from the 100kW plant and correlated with the results from the 50 and 500kW plants. The vast knowledge gained from the process during the last 10 years has given a firm design basis for the new 6MW plant.

The safety analysis has also given input to the design. Based on this and the recommendations in 'Guideline for Safe end Eco-friendly Biomass gasification' [1], the different gasifier vessels and connecting pipes have been dimensioned for 10 barg to be able to contain a possible gas explosion. The largest vessel is, however, dimensioned for a lower pressure and is equipped with pressure relief equipment.

All vessels are ceramic lined internally with a steel pressure shell outside.

5.9 Product gas utilisation

The gas from the gasifier is to be burned in the ASV2 boiler unit. The gas is 650°C when it leaves the gasifier and is only cleaned using a hot cyclone which extracts 90-95% of the particles in the gas. The gas is transported in a gas duct to a separate dedicated burner placed in the boiler front wall. Due to the relatively small size of the gasifier, the gas could be burned in the boiler in a more simple way, but a solution with a separate burner was chosen in order to gain knowledge that can be used for future scaled-up plants.

The burner will be placed in the middle of the boiler so that coal burners placed below the gas burner can support the ignition of the gas and the coal burners above can ensure burnout.

Air for the burner will be taken from the existing air system for the boiler.

During the first phase of the project, including commissioning of the gasifier, the gas will be flared off on top of the gasifier. Later, the gas duct to the boiler and the gas burner will be installed.

[1] The guideline is a result of project no. EIE-06-078 supported by the Intelligent Energy for Europe programme and was co-funded by the European Commision.

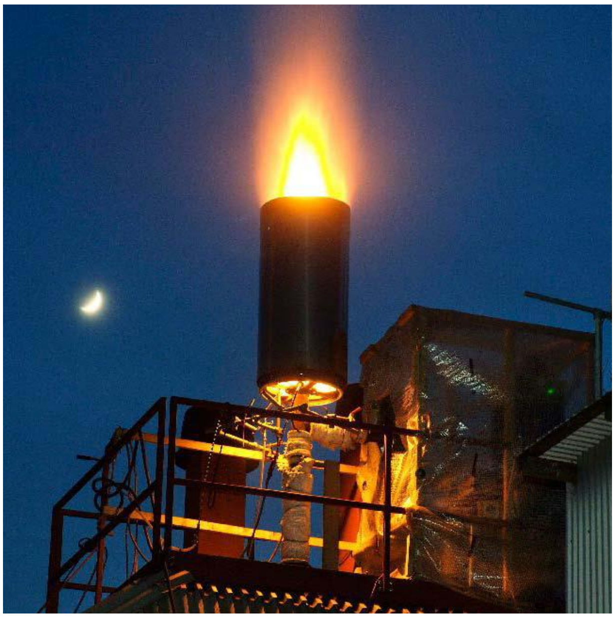

Figure 8: Flaring off gas at 500kW plant at DTU

5.10 Auxiliary equipment

5.10.1 Buildings

The whole plant is designed to be placed outdoor so that no buildings are necessary. The process is under slight overpressure and CO will be emitted to the surroundings in case of a leak. It was considered the safest solution to place the gasifier outdoor. The cost could thereby also be reduced.

Electrical equipment is placed in a container and a site hut is used as the local control room next to the gasifier. Later on when the plant is fully automated, it is anticipated to be controlled from the central control room at Asnæs Power Station.

5.10.2 Cooling water

Cooling of the ash and feeding screw is needed. A separate secondary cooling system is designed for this purpose. For safety reasons it is important to be able to control and limit the amount of water that will enter the process in case of a leak.

In the demonstration plant, the surplus heat will not be utilised but will be cooled with sea water. The plant is kept as simple as possible to improve the availability and lower the investment. In scaled-up plants the waste heat from the ash system will be utilised for eg preheating of air or integrated with the power plant steam cycle.

5.10.3 Nitrogen

When the gasifier is shut down or in case of a gas leak, it is important to flush the gas out of the system to the flare. A liquid nitrogen tank will be placed next to the gasifier for this purpose. N_2 is also needed as purge gas several places during operation.

5.10.4 Air and water system

Air is needed various places in the process for conversion of the char and for circulation of bed material between the reactors. The air system is based on a single large blower and a manifold from where air is distributed to the different consumers. For safety reasons it is important not to add air to the process uncontrolled when it has been shut down to avoid gas explosions. This is easier controlled when there is only one blower. It is, however, not so energy efficient, but this has not been the primary concern when designing the demonstration plant.

Steam will be added to the process for conversion of char and temperature control of the process. The steam generation will be made simple by using oil, gas or electricity. In future scaled-up plants the steam will be made based on waste heat from the gasifier or the power plant.

5.10.5 Start-up burner

A single oil or gas-fired start-up burner is used for cold start of the plant. The start-up time is fairly long due to the ceramic lining and heavy bed material in the plant. No special effort has been made to be able to make a faster or less expensive start-up of the demonstration plant. Several solutions for optimised start-up are anticipated to be implemented at a later stage.

6. Construction project

6.1 Dividing into phases

Based on the findings from the design project, a construction project was designed which included not only construction of the demonstration plant but also a test/operation period and the necessary associated activities needed for further development and commercialisation of the technology.

The establishment, test and operation of the demonstration plant have been divided into three phases to lower the economic risks of the project and to be able to get the first results from the demonstration plant as early as possible.

The findings from the design project have resulted in a project layout consisting of three periods:

To reduce the economic risk of such a demonstration project, two technical milestones are included, which have to be passed to proceed to the next period.

Phase 1: Upscaling
Focus will be on engineering and construction of the gasifier. The gasifier will not be integrated with the power plant, and it will only be equipped with the most necessary control and instrumentation equipment needed for safe operation. The purpose is to demonstrate that the gasifier also works in a scaled-up version.

Phase 2: Integration
When the gasifier has been successfully commissioned, it will be integrated with the power plant, and focus will be on optimised char conversion, separation of ash, gas transport, burner design, etc. The control and instrumentation system will be improved and connected to the power plant. From this period on, the product gas will be used to produce power to the grid.

Phase 3: Demonstration
The purpose of this period is to equip the gasifier with the needed instrumentation and logic to demonstrate safe and reliable automatic operation over an extended period. The purpose is to demonstrate reliability and to test wear and tear. Furthermore, the plant and the test results will be the reference for future full-scale plants.

6.2 Time schedule

Funds for the design project were applied for in the September 2008 ForskEL call. The project was started up in January 2009 and the original end date was March 2010. The end date was later postponed to May 2010 to allow for a better overlap between the design project and the construction project.

The key milestone for the design project was that sufficient data should be gathered so that an application for funds could be handed in for the September 2009 ForskEL/ForskVE call. Also an environmental application was to be handed in during the autumn of 2009 so that the following construction project could be started sooner.

In the design project, delivery times for key components for the demonstration plant were investigated at suppliers and construction times were estimated. In phase 1 and phase 2, two relatively short test periods are anticipated for commissioning and testing of the gasifier, auxiliary equipment and the connection to the boiler. After some anticipated adjustments and improvements, an extended test period is scheduled for 2013.

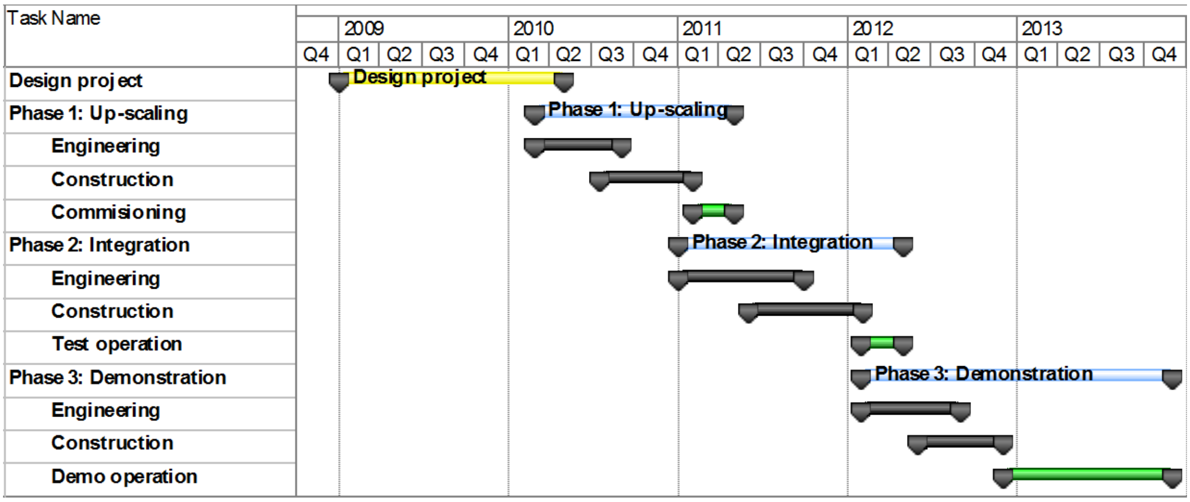

Figure 9: Demonstration project time schedule

6.3 Economy

Each subsystem has been thoroughly analysed to find the most optimal overall solution for the demonstration plant. Considerations have also been made to ensure that the solutions could be used for future scaled-up plants.

The final economy for the design project divided on partners has been:

Project partner	**Spent (1000 x DKK)**
DONG Energy	4,637
Danish Fluid Bed Technology	1,232
Risø-DTU	346
Total	**6,215**
Of which ForskEL grant	3,200

The cost of the demonstration plant has been evaluated using input from suppliers of different components and experience from previous construction projects within DONG Energy. The below figures for the three phases include man-hours, purchase of equipment, on-site construction, commissioning and test operation of the gasifier in the above-mentioned periods.

Phase	Budget million DKK
1: Upscaling	36.9
2: Integration	29.2
3: Demonstration	11.5
Total	**77.6**

The budget includes a fairly large amount of man-hours because this is a first of a kind demonstration plant where it is not possible to use standard components for a lot of solutions. During the first two phases where the plant is manually operated, a lot of man-hours for operation are also anticipated.

Future large plants will be less expensive.

7. Dissemination

The technology and the project have been presented at the following occasions:

- An article was submitted to the 18th Biomass conference and exhibition in Lyon, France, 3-7 May 2010 (attached as appendix 1), and an oral presentation was made
- The project has been mentioned several times in Biopress and FIB ('Forskning i Bioenergi') magazines
- An article was brought in the magazine 'Ingeniøren'
- The project has also been mentioned more briefly in other printed and internet media
- A webpage for the technology has been launched at www.LTCFB.com.

The technology has not been promoted very much in this project period, primarily because DONG Energy wants to protect the technology and their investment and no large commotion is planned until the demonstration plant is operational. The negotiations for handing over of the rights with Sto-holm lasted until December 2009 and no effort was put into commotion during the final months of the negotiation period.

8. Business strategy

DONG Energy bought the rights to the LT-CFB technology from the inventor Peder Stoholm, DFBT Aps, in December 2009. The aim is to use the technology on DONG Energy-owned power plants, but also to sell gasifiers to others at a later stage. It is anticipated that the technology will be transferred to a new company at a suitable time. Some potential customers have been identified and a few have been contacted. More efforts will be put into this when the demonstration plant is in operation.

DONG Energy intends to protect the technology and develop it further and submit new patent applications along the way.

An updated competitor analysis has indicated that the technology still is unique and that no other technologies aim at the same niche.

The Low Temperature CFB gasifier – 100 kW_{th} tests on straw and new 6 MW_{th} demonstration plant.

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ABSTRACT: The novel "Low Temperature Circulating Fluidised Bed" (LT-CFB) gasifier is briefly described together with results from first gasification and gas cleaning tests with a new 100 kW_{th} LT-CFB test plant located at the Technical University of Denmark (DTU). Plans for a new 6 MW_{th} demonstration plant are also presented. A first and still major purpose of the LT-CFB gasifier is "indirect" co-firing of difficult biomass and waste fuels at coal fired power plants. In this case simple hot gas cleaning prior to the boiler can be based on just a hot secondary cyclone, i.e. cooling of the product gas is avoided. The necessary fuel flexibility is achieved by designing the gasifier in a way that allows for good char conversion in spite of typically keeping the char gasification temperature at only around 750°C. High retention of e.g. K, P and Cl in the separated bio-ash is possible due to an even lower gas exit temperature from the gasifier (~650°C). Furthermore, a low tar dew point as well as a low content of PAHs in the separated ash are achieved due to initially pyrolysing the bio-fuel at low temperature and retention time. Evidence for all of these advantages as well as a first scale up have been established by erecting and testing a first 50 kW and a 500 kW LT-CFB plant. The test fuels have mainly been high alkaline wheat straw, hen manure, pig manure, biogas residue fibers and residue fibers from a food processing industry using citrus shells and seaweed. During the reported first 100 kW tests, again only ordinary silica sand and no additives was used as bed material, and in spite of that, no agglomeration problems occurred. Gas cleaning was for the first time performed by not only dynamic ash separation in a cyclone but thereafter also by cooling and filtration of the gas in a bag filter. By operating the bag filter at around 300°C a relatively low cost glass fiber type of filter bag could be applied and potential problems due to tar condensation in the cooler and filter could be avoided. The reported first tests with this type of extended gas cleaning system indicate that it will be possible to produce an essentially dust free but still tarry gas, which can be utilized for co-firing very high shares of bio- and waste fuels in not just coal fired boilers but also in boiler plants designed only for oil and natural gas. Moreover, many other applications are possible. Funding for a new 6 MW LT-CFB demonstration plant has been secured and this plant will be commissioned at a DONG Energy owned Danish coal fired power plant in the beginning of 2011.
Keywords: biomass, waste, conversion, co-firing, gasification, circulating fluidised bed (CFB).

1 INTRODUCTION

One of the most cost effective options for substituting fossil fuels and for reducing the CO2 emission is co-firing biomass and waste in existing coal fired boilers. However, most of such fuels contain low melting and corroding inorganics such as KCl and may therefore cause severe problems if co-fired (directly) into the boilers at especially the most energy efficient power plants. Problematic depositions as well as corrosion may be the result on especially the very hot super heater tubes and a potential high dust de-NOx catalyst may suffer premature de-activation. Moreover, the options for making use of the bio- and coal ashes will be limited if the ashes are mixed. The Low Temperature Circulating Fluidised Bed (LT-CFB) gasifier was designed in order to overcome these problems.

Most tests with a first 50 kW plant and a later 500 kW plant were on high alkaline straw and various types of animal manure which also included biogas residue fibers [1-3].

In a new 100 kW LT-CFB test plant presented below, the fuel has again mainly been cereal straw but also residue fibers from a Danish industry producing pectin and carageenan based on respectively citrus shells and seaweed.

Based on R&D conducted during the last more than 10 years, the next step will be demonstrating a 6 MW_{th} LT-CFB co-firing plant at the DONG Energy owned coal fired Asnaes power station near the Danish city of Kalundborg.

2 LT-CFB GASIFIER

2.1 LT-CFB concept with simple hot gas cleaning

The LT-CFB gasification process has been described in earlier publications [1-4] and therefore a preferred version will here only be described shortly (see Fig. 1).

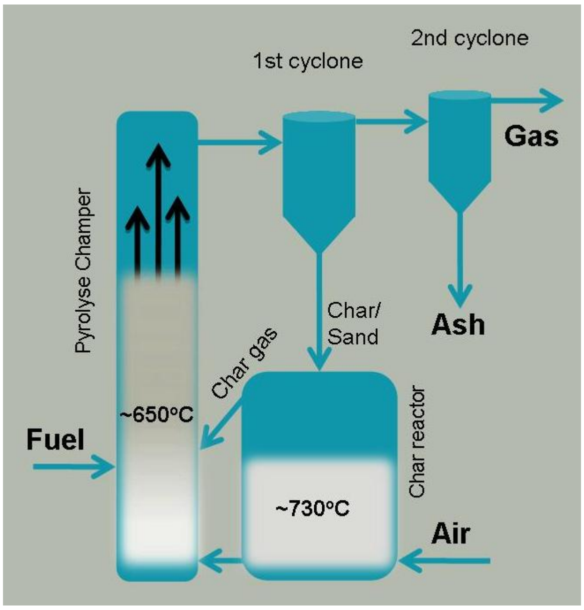

Figure 1: LT-CFB flow diagram (simple version with a hot secondary cyclone for gas cleaning).

Small fuel particles enter the pyrolysis chamber and are rapidly pyrolysed at e.g. ~650°C due to good thermal contact with mainly re-circulated sand and ash particles. Due to the low temperature and retention time in the pyrolysis chamber essentially only light tars and nearly no PAH are formed.

The residual char, pyrolysis gasses and inert particles are flowing upwards to the primary cyclone, which separates the char and inert particles to a bubbling bed char reactor. Here the char is gasified at typically ~730°C using mainly air. Some steam or water may also be added in order to improve the conversion of char. Due to the low and very stable temperature, only little ash melting takes place and therefore agglomeration problems can be avoided without using additives.

The char gas produced and fine ash particles leave the top of the char reactor and enter the pyrolysis chamber, where the char gas contributes to the high gas velocity in the upper part. Heavier particles re-circulate to the pyrolysis chamber from the bottom of the char reaction chamber while acting as a heat carrier. Heat from the mainly exothermic reactions in the char reactor is this way transferred to the mainly endothermic processes in the pyrolysis chamber.

Due to the heat absorption in the pyrolysis chamber, the exit stream out of the pyrolysis chamber has an even lower temperature compared to the temperature in the char reactor. Consequently, nearly all alkalines and similar ash components are retained in solid state and therefore such components are separated roughly as efficient as the particles entering the cyclones.

Neither heating nor heat absorption surfaces are needed anywhere in the process and of course all complications and potential problems related to such surfaces are therefore avoided.

Ash particles may re-circulate several times but eventually the main part will typically escape through the primary cyclone and be separated by the more efficient secondary cyclone. A further coarser ash stream may be drained from the bottom of the gasifier, and in these two ways, typically around 95% of the ash can be retained.

2.2 Co-firing and other applications

The hot gas cleaned in this simple way can be added to the combustion chamber of existing as well as new coal fired boilers and compared to direct co-firing. The following advantages can be achieved:

- Low value and difficult fuels such as straw, young energy crops, animal manure, biogas residue fibers, sewage sludge and similar waste streams may be co-fired.
- Only small changes to the boiler are needed.
- Around 95% of the bio-ash, including e.g. K and P can be kept out of the boiler and therefore fouling and corrosion on especially the hottest super heater tubes can be reduced.
- Deactivation of a potential high dust de-NOx catalyst can be reduced.
- Coal and biomass ashes are nearly obtained as separate streams, which greatly improves the possibilities for utilizing the respective ashes.

Some of these advantages can be transformed to, that a much higher share of bio-fuel can be co-fired and/or - in the case of new plants - higher steam data can be applied. Hence, the use of low value fuels for producing electricity at efficiencies around 45 % is within the scope of the LT-CFB gasifier which is expected to be commercially feasible in sizes from around 5 to at least 100 MW fuel input. Of course higher capacities can be reached by several parallel units which can also be interesting in the case where the ashes from different simultaneously co-fired bio-/waste fuels should not be mixed.

Based on more intensive cleaning, the LT-CFB gas can also be used for more demanding applications such as for oil and natural gas fired power plant boilers. Moreover, various possibilities of producing liquid fuels/products as well as bio-char are also considered.

2.3 The test plants at DTU

Initially a 50 kW LT-CFB test plant was built at DTU and operated on a range of different fuels including high alkaline straw, pig manure fibers, and hen manure [3]. In 2004 the 10 times up-scaled, fully refractory lined and partly automated 500 kW plant shown in Fig. 2 was commissioned and within the following years it was tested on straw, animal manure and biogas residue fibers [1-2].

Figure 2: 500 kW LT-CFB test plant at DTU.

Figure 3: 100 kW LT-CFB gasifier at DTU. The gasifier is the parts in alu-folio, while the blue barrels are the (elevated) fuel bin and the bin for ash separated by the secondary cyclone.

Also the new 100 kW plant, shown in fig 3, was built and initially operated at DTU, but it will be moved to Risø-DTU (near Roskilde) during 2010. The 100 kW plant is not only larger but also somewhat optimized and more automated compared to the first 50 kW plant which it replaces.

Compared to the 500 kW plant, the 100 kW plant is much easier to use for performing short term tests. Moreover, the 100 kW plant is designed for allowing easy modifications as well as easy relocation in order to also perform tests on fuels like meat and bone meal, household waste and sewage sludge which are not allowed to be handled and gasified at the premises of DTU.

2.4 First 100 kW tests

As can be seen in table 1, the 100 kW plant has been operated 8 times in the period May 2009 to January 2010. The individual tests lasted up to 3 days including ramping up the temperature and load. In the longest test (no. 8 in January 2010), the temperature in the char reaction chamber were above 700°C in 52 hours, and al of the recent tests with the 100 kW plant sums up to approximately 160 such operating hours.

Table 1: All of the present 8 test with the new 100 kW LT-CFB plant (hm=hammer milled, p&c=pelletised and crushed, SC=secondary cyclone, POX=partial oxidation)

Test no. and date	Fuel	Operating hours at beyond 700°C in char gasifier / hours with bag filter	Type of gas cleaning	Comments
1) 28. May 2009	Straw, hm	0 / 0	SC	Mostly feeding problems
2) 24.-25. June 2009	Straw, hm	4,5 / 0	SC	Load limited by feeding problems
3) 8.-9. July 2009	Straw, p&c	22 / 0	SC	First long and stable operation of the 100 kW LT-CFB gasifier
4) 8.-9. Sept. 2009	Straw, p&c	17 / 1	SC, cooler and filter	1 hour test of slip stream cooler and filter. Some new feed system problems solved.
5) 23.-24. Sept 2009	Straw, p&c	28 / 6	SC, cooler and filter	Long and efficient operation on straw and first long and successful cooling and filtration test.
6) 17.-18. Nov. 2009	Residue fibers mainly from citrus shells, p&c	25 / 7	SC, cooler and filter	Up to > 110% load at high efficiency on this new LT-CFB fuel. Gas cooling and filtering again sucessful
7) 15.-16. Dec. 2009	Residue fibers mainly from citrus shells, p&c	12 / 6	SC, cooler and filter	Leak from primary cylone day 1. Error in PLC program day 2.
8) 13.-15. Jan. 2010	Straw, p&c	52 /16	SC, cooler, filter and POX	Longest stable and efficient operation on straw. Filter exit ducht (but not cooler and filter) eventually blocked due to bad electrical heat tracing

The fuels were straw (test no 1-5 and 8) and a mixture of residue fibers from an industrial production of pectin and carrageenan (test no 6 and 7) which is extracted from respectively citrus shells and seaweed. In the first two tests the straw was just hammer milled, while in all of the later 6 tests the fuel was pellets crushed to a max. size of approx. 3 mm. Some main data for the fuels used in tests no. 3-8 is included in table 2.

In the tests on straw the gasification agent was air and around 5 weight % water, while only air was applied during the test no. 6 and 7 on residue fibers.

As in all earlier tests with the 50 and 500 kW plants, only ordinary silica sand and no additives were used as bed material. In order to better represent long term operation the bed material was reused through all 6 tests on straw and also from test no 6 to 7 on residue fibers.

Table 2: Data for fuels in 100 kW LT-CFB tests nos. 3-8.

Fuel	Moisture as received %	Ash in dry matter %	P / K / Cl in dry matter %	Lower heating value, as received MJ/kg
Straw for tests nos. 3-5	7.7	5.2	0.05 / 1.0 / 0.4	16.01
Residue fibers for tests nos 6 and 7	8.3	13.1	0.08 / 0.5 / 0.061	14.92
Straw for tests no. 8	8.3	5.9	0.1 / 1.1 / 0.24	15.82

3 100 kW TEST RESULTS

3.1 Overall

The overall experience from these first 8 tests is that the 100 kW plant operates similar to the two former LT-CFB plants.

As can be seen from the table 1 above, the very first two tests in May and June 2009 on loose hammer milled straw did not result in operation at full load.

The new choice of fuel preparation, -i.e. crushed pellets - for tests numbered 3 to-8 allowed better fuel feeding and this led to the first operation at close to full load at July 8-9, 2009. During the test no. 4 some further experiences with the new plant was gained and the functionality a slip stream gas cooling and bag filter based gas cleaning system was initially tested.

Some further selected result from the last 4 tests no. 5-8 are mentioned in the following.

3.2 Process stability and agglomeration

A very high process stability have been achieved many times during previous tests with the 50 and 500 kW plants and now again with the 100 kW plant. As an example Fig. 4 shows 3 important process temperatures during the last 6 hours of test no. 8.

The highest of the 3 temperatures is measured in the char reaction chamber. Here it is important to allow for efficient char conversion but also to always avoid temperatures that will lead to disturbances due to formation of agglomerates in the bed material.

The intermediate temperature is measured near the point of fuel feeing in the pyrolysis chamber. Here it is important to achieve an efficient pyrolysis (low char residue) but a too high temperature may result in formation of PAHs due to tar cracking.

The lowest temperature in fig 4, - measured between the two cyclones – must be so low that nearly all e.g. KCl is kept in solid state so that it can be separated from the product gas.

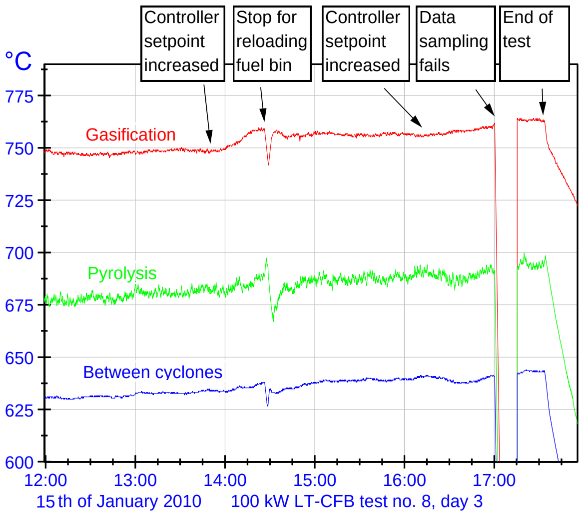

Figure 4: Important process temperatures from the last 6 hours of 100 kW LT-CFB test no. 8 on straw.

The first mentioned maximum process temperature (in the char reaction chamber) was precisely controlled just below 750°C, in most of this test no. 8, but eventually the temperature was increased to just above 760°C. This was the result of loading a slightly higher set point to the PLC two times, which was done at approximately 14:00 and 16:20. The purpose was mainly to evaluate the dynamics of the temperature controller and to see if disturbances due to agglomeration would appear while eventually operating just approximately 10°C below the melting point of KCl.

The lacking temperatures shortly before deliberately stopping the test with an empty fuel silo (at 17:40) was due to a break down of the data acquisition (Labview in Windows XT), but as can be seen, the PLC still controlled the process nicely after these exciting 20 minutes with most process data being invisible to the operators.

No signs of agglomeration was discovered even though an analysis on a sample of the bed-material showed that the content of potassium was 8 %, which is the highest level ever measured after any of the many earlier LT-CFB tests. The high level is a consequence of reloading the bed material through all of the 100 kW tests on straw.

Notice also the disturbance of the temperatures just before 14:30 in fig 4. This is due to an automatic stop lasting 1-2 minutes while automatically refilling the fuel bin. After such a stop the addition of air and fuel is immediately resumed at the full load settings. Continues fuel feeding will of course be possible in commercial LT-CFB plants and was also done during the former 500 kW tests. However, e.g. in the case of operating commercial LT-CFB plant only during peak load hours it is interesting that especially large and well insulated gasifiers can probably perform similar fast restarts after up to several days of hot stand by.

3.3 Energy efficiency

A high efficiency, i.e. a low content of unconverted carbon in the ash, could be achieved at a higher fuel energy input of the residue fibers compared to straw. In both cases the total oxidiseable carbon was around 2 % of the fuel input (kg carbon/kg fuel) which compares to 3-4 % energy loss. However, the fuel energy input (LHV) was typically only 90-100 kW on straw and 100-110 kW on the residue fibers.

The same tendency of allowing somewhat higher energy input than on straw has earlier been seen during tests on manure and biogas residue fibers even though the feed rate of especially the biogas residue fibers was much higher, which was due to an ash content in dry matter of up to more than 40 %,

3.4 Gas cleaning

As can also be seen from table 1, the gas was initially cleaned by the hot secondary cyclone in all of the conducted 100 kW tests. This way ash retention at the also earlier reported level of around 95 % could be achieved. Such level of ash retention will allow for a much higher share of co-firing biomass and waste fuels into coal fired boilers. However, in boilers only designed for and using natural gas the remaining around 5 % ash in the LT-CFB product gas would be at problem in several ways including fouling and super heater corrosion and usually a large dust filter would have to be added down stream the boiler.

For these reasons and for promoting even further possible applications of the LT-CFB gasifier, all of the test nos. 5-8 also comprised cooling and bag filtering a small slip stream of the gas coming from the secondary cyclone.

In order to avoid potential severe depositions in the cooler and filter due to condensation of tar, the filter was in all cases operated at around 300°C.

The general experience was that increased pressure loss did not occur in neither the cooler nor the filter, i.e. back flushing the filter approximately every approximately 1 hour continued to be enough for each time reestablishing the initial pressure loss over the filter.

This first experience with cooling and filtering the LT-CFB gas indicates that a number of further system applications for LT-CFB gasifier will be feasible.

However, a number of the thinkable applications will not only require an essentially dust free but also an essentially tar free gas. A first step in this direction may be partial oxidation (POX) and therefore such a test was prepared in the test no 8. The test which was conducted on the filtered gas gave a positive indication, i.e. a dramatically reformed gas was the result, but the POX test became very short and must therefore be repeated at a later occasion.

4 DEMONSTRATION AND COMMERCIALISATION

4.1 6 MW demonstration plant

The next step will be demonstration of a new 6 MW_{th} LT-CFB co-firing plant, which is now financially secured and the major parts are currently being procured. The location is the DONG Energy owned coal fired Asnaes power station. The gasifier with auxiliary equipment is illustrated in figure 5 below.

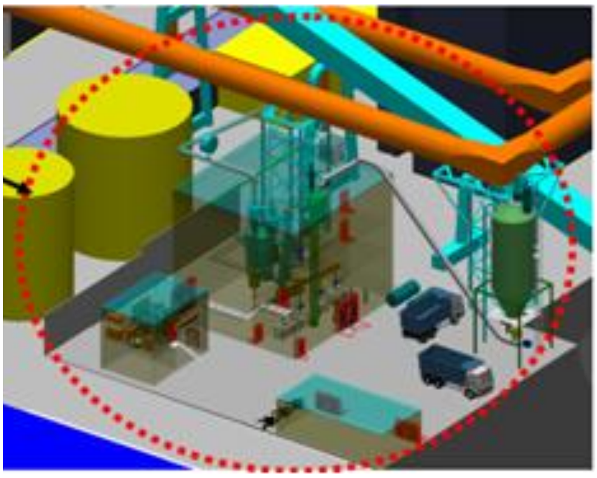

Figure 5: Computer model of the 6 MW_{th} demonstration plant at Asnaes power station.

The demonstration plant will be commissioned early in 2011. During the first short tests on straw the product gas will simply be flared, then follows some tests after adding the gas connection to the boiler. Finally, the plant will be more thoroughly automated and demonstration comprising long term operation on various fuels will be performed. A 3 year test programme has been planned which will contribute with more knowledge about especially scaling effects, wear and tear of materials and O&M procedures and expenses.

4.2 Commercialization

Along with DFBT, DTU, FORCE Technology and Anhydro, DONG Energy has participated in most of the previous development of the LT-CFB process as a project partner and recently DONG Energy acquired DFBTs rights and know how for the LT-CFB technology. On the further basis of experiences gained from the demonstration project, it is the intention of DONG Energy to implement further up-scaled LT-CFB co-firing gasifiers on own power plants. Moreover, the goal is commercialisation which may also comprise other viable LT-CFB versions and system applications.

5 CONCLUSION

Results gained from the first operation of a the new 100 kW LT-CFB test plant built and initially operated at DTU confirm earlier 50 and 500 kW test results showing that the LT-CFB gasifier is capable of efficiently gasifying difficult and/or low value bio- an waste fuels. Furthermore, it has been experimentally confirmed that besides simple gas cleaning based on ash separation in just a hot cyclone it is also possible to more efficiently clean the tary gas using a bag filter operated at around 300°C.

The next step will be to demonstrate a 6 MW_{th} LT-CFB co-firing plant which is now decided, financially secured and being procured. It will start up at a DONG Energy owned coal fired power plant early in 2011.

On this important further basis its is the intention of DONG Energy to not only implement further up-scaled LT-CFB gasifiers on further power plants of its own, but also to commercialise the technology.

6 ACKNOWLEDGEMENTS

The PSO R&D program conducted by the Danish transmission system operator Energinet.dk and the Danish Energy Agency economically supports the ongoing R&D efforts.

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DFBT

DONG energy

Bilag til slutrapport for PSO-ForskEl projektnummer 2009-267

LT-CFB demonstration plant, Phase 1

100 kW LT-CFB forsøg nr. 8

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November 2010

Indhold:

1. Indledning

1.1 Aktuelle projekter og finansiering

Denne rapport omhandler det sidste af foreløbigt i alt otte LT-CFB forgasningsforsøg, som fra foråret 2009 til januar 2010 er blevet gennemført med et nyt 100 kW LT-CFB forsøgsanlæg på DTU. De otte forsøg er gennemført som led i de følgende tre projekter:

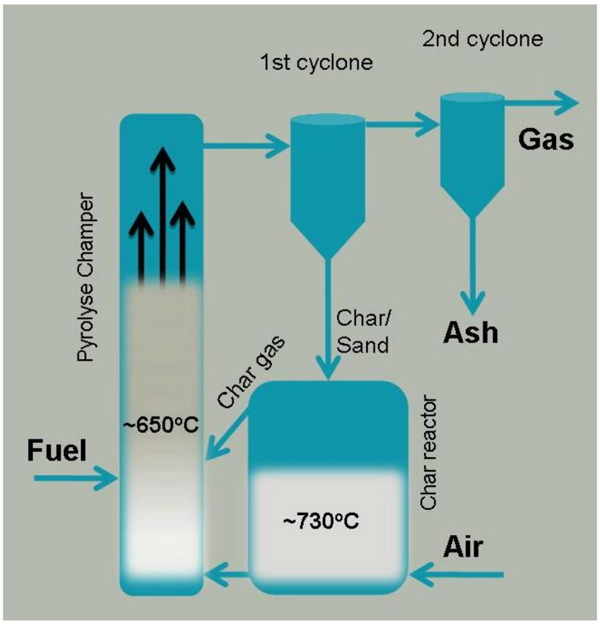
1. PSO-ForskEl-2007-7504 projektet "LT-CFB, Videreudvikling og kommercialisering"
2. PSO-Eranet-2008-1-10036 projektet "Tar removal from low-temperature gasifiers"
3. PSO-ForskEl-2009-10267 projektet "LT-CFB demonstration plant, Phase 1"

Finansieringen af det seneste 100 kW LT-CFB forsøg stammer overvejende fra det sidstnævnte projekt. Dog var visse gennemgående aktiviteter, vedrørende primært videregående gasrensning og automatisering, finansieret af de to tidligere projekter. De forudgående syv 100 kW LT-CFB forsøg er ligeledes gennemført og rapporteret som led i de to tidligere projekter.

LT-CFB aktiviteterne videreføres nu i regi af primært et PSO-2010 projekt, der som hoved-punkter omfatter etablering og demonstration af et 6 MW LT-CFB anlæg i tilknytning til Asnæsværkets blok 2.

1.2 LT-CFB konceptet

En simpel version af LT-CFB forgasningskonceptet fremgår af Figur 1:



Figur 1: LT-CFB forgasningskoncept

Brændslet introduceres i et hurtigt fluidiseret pyrolysekammer, hvor cirka 80 % af brændselspartiklernes organiske del næsten momentant går på gasform. Den resterende koks og cirkulerende inertpartikler i pyrolysekammerets afgående gasstrøm separeres af en primær partikelseparator og føres ned i en koksforgasser. På denne måde kan koksomsætningen få en god opholdstid i den langsomt fluidiserede koksforgasser, hvorved den maksimale procestemperatur typisk kan holdes under 750 °C, og problemer, der relaterer sig til askesmeltning, minimeres.

Også den endnu lavere temperatur i pyrolysekammeret bidrager til at holde delvist fordampelige stoffer som KCl på fast form, hvilket er en forudsætning for, at disse stoffer simpelt kan separeres sammen med asken. Dette f.eks. blot ved hjælp af den sekundære cyklon, se Figur 1. Den lave og velkontrollerede temperatur samt kort gasopholdstid i pyrolysekammeret betyder endvidere, at man stort set undgår dannelse af tunge tjærestoffer og således også PAH i den producerede aske.

Når der f.eks. til samfyring på naturgasfyrede kedelanlæg kræves en meget støvfattig gas, er et højeffektivt partikelfilter nødvendigt, og forud for dette behøves en rågaskøler. Her er det en fordel, at LT-CFB gassen stort set ikke rummer hverken delvist fordampede askestoffer eller tunge tjærestoffer. Det er derfor muligt at afkøle gassen til nær tjæredugpunktet (f.eks. 300 °C) for derefter at benytte et almindeligt tilgængeligt partikelfilter.

Når der således kan opnås en stort set partikelfri gas, er der også bedre mulighed for efterfølgende at reformere gassen med sigte på anvendelser, der kræver en tjærefattig gas.

Blandt LT-CFB forgasserens yderligere anvendelsesmuligheder er diverse typer combined cycle anlæg samt produktion af syntesegas og/eller såkaldt bioolie og/eller biokoks.

Se i øvrigt en række mere omfattende præsentationer af LT-CFB forgasningskonceptet i f.eks. [Stoholm et al, 2007] og i den af DFBT indleverede patentansøgning [Stoholm, 1998].

1.3 Primære fordele

LT-CFB forgasseren har flere egenskaber af overordnet betydning. Disse omfatter brændselsfleksibilitet, adgang til simpel gasrensning og bevaring af næringsstoffer på plantetilgængelig og/eller syreoplukkelig form. Yderligere kan nævnes muligheden for lavt kulstoftab trods lave procestemperaturer og lavt indhold af PAH i asken. Ingen af de nævnte egenskaber er en selvfølge for fluid bed forgassere.

Brændselsfleksibiliteten er vigtig, fordi en stor del af de bio- og affaldsbrændsler, der er nødvendige for at etablere en både tilstrækkelig, stabil, bæredygtig og mere CO_2-neutral energiforsyning, ofte medfører en række problemer i energiproducerende anlæg. Problemerne er ikke mindst udtalte for unge landbrugsafledte brændsler anvendt til højeffektive elproducerende anlæg i rationel og økonomisk skala, dvs. i kraftværksregi.

Simpel gasrensning er også vigtig, fordi gasbehandlingen efter de fleste kendte biomasse-forgassere, og herunder endda også forgassere til relativt uproblematiske træbrændsler, har vist sig at være meget problemfyldt, især, når man fra starten sigter på noget af det sværeste, så som at producere gas til et motor-generatoranlæg. Her er den store udfordring at opnå et meget lavt tjæreindhold i gassen. Der findes gode forgasningsbaserede løsninger, men ikke hvis kravene også er stor størrelse og brændselsfleksibilitet, så f.eks. også halm med højt indhold af KCl kan benyttes.

Når LT-CFB forgasseren anvendes til det oprindeligt primært påtænkte formål, nemlig samfyring med biomasse og affald på eksisterende kulfyrede kraftværker, er det en stor fordel, at kulkedlen og således også kulasken i høj grad kan friholdes for delvist fordampelige stoffer som K og P. Selv ved blot varm cyklonrensning er der mulighed for en markant højere andel af indfyret biobrændsel og/eller højere dampdata og deraf følgende højere elvirkningsgrad. For større kedler forudsætter en høj bio-andel dog naturligvis en tilstrækkelig opskalering af LT-CFB forgasseren og/eller anvendelse af flere parallelle forgassere.

Ved en mere effektiv filtrering af LT-CFB gassen øges de fordele, der kan opnås som følge af separationen af bio-aske og det bliver f.eks. også muligt at benytte ikke-asketolerante kedler så som naturgaskedler til biomasse og affald.

1.4 LT-CFB forsøgsanlæg

Der er tidligere gennemført en lang række forsøg på de tre LT-CFB forsøgsanlæg, der gennem de seneste godt 10 år er blevet opført på DTU i Lyngby. De tre forsøgsanlæg har været udlagt for en indfyret brændselseffekt på hhv. 50, 500 og senest 100 kW.

En første afprøvning og optimering af forgasningskonceptet blev opnået med 50 kW anlægget, hvorefter resultaterne fra 500 kW anlægget påviste muligheden for den første markante opskalering med en faktor 10. Det blev også vist, hvordan processen kan etableres i en fuld keramisk foret og således langtidsholdbar konstruktion. Endelig blev det PLC-regulerede 500 kW anlæg efterhånden delvist automatiseret, ligesom der blev fundet løsninger på håndtering af store mængder brændsel og aske samt effektiv affakling af gassen.

De to tidligere 50 og 500 kW forsøgsanlæg er blevet beskrevet i tidligere publikationer. Se f.eks. [Stoholm et al, 2007].

Det seneste 100 kW anlæg, som ses i Figur 2 og 3, er i løbet af 2008 og foråret 2009 blevet etableret i Biomasseforgasningsgruppens tidligere forsøgshal på DTU. 100 KW anlægget kan ses som en procesteknisk opdateret og automatiseret afløser for 50 kW anlægget. Blandt forbedringerne af selve forgasseren kan nævnes, at der – ligesom i 500 kW forgasseren – er indskudt en såkaldt mellemreaktor i partikelreturkanalen mellem koksreaktoren og pyrolysekammeret. Derved opnås blandt andet en supplerende koksomsætning under omtrent samme procesbetingelser som i koksreaktoren.

Figur 2: 100 kW LT-CFB forgasser på DTU, med påbygget PLC-skab, fritstående kontrolpanel til højre, set fra sydøst.

Figur 3: 100 kW LT-CFB forgasser på DTU, med brændselsindfødningssilo (blå øvre) og asketønde (blå nedre) - set fra 1. sal i forsøgshallens nordlige ende.

Både den mindre størrelse og den meget lettere konstruktion i forhold til 500 kW anlægget gør det mindre ressourcekrævende at gennemføre både forsøg og nye procestekniske forbedringer.

Under drift doseres brændselsstrømmen af en omdrejningsreguleret dobbeltsnegl placeret i bunden af brændselssiloen. Siloen er ophængt i vejeceller, hvorved brændselsstrømmen kan vurderes ud fra gradienten på det aftagende vejecellesignal.

Forsøgsanlægget er foreløbigt blevet kombineret med gasrensningsudstyr placeret nedstrøms sekundærcyklonen. Der er tale om en fuldstrøms spraykøler og derefter en konvektionskøler, et posefilter og et kammer, hvori gassen kan reformeres ved partiel oxidation (POX). Konvektionskøleren, posefilteret og POX-kammeret gennemstrømmes dog kun af en mindre del af gassen, som efter en centrifugalblæser genforenes med hovedgasstrømmen. Derefter affakles den samlede gasstrøm over forsøgshallens tag. Gasstrømmen gennem konvektionskøleren, posefilteret og POX-kammeret måles ved hjælp af en blænde og reguleres ved omdrejningsregulering af centrifugalblæseren.

I konvektionskøleren gennemstrømmer gassen et rør som i modstrøm køles udvendigt af elektrisk forvarmet luft.

Posefilteret, der er forsynet med udvendige el-varmebændler og isolering, ses i Figur 4. Filtret rummer en enkelt glasfiberbaseret pose fra firmaet 3M. Som maksimal anvendelses-temperatur anføres 371 °C. Under drift kan posen renses ved manuelt aktiveret ”pulsning” med nitrogen.

Figur 4: Delstrøms posefilter

I det ligeledes isolerede og termostaterede POX-kammer kan gassen reformeres ved tilførsel af en lille strøm af elektrisk forvarmet luft.

Gasrensningssystemet er nærmere omtalt i slutrapporten fra PSO-Eranet-2008 projektet [Zwart et al, 2010].

PLC regulering (Siemens) og mulighed for næsten fuldautomatisk drift er et andet fælles træk med 500 kW anlægget. Både PLC-programvalg (opvarmning, drift, nedlukning, mv.) og manuel regulering af brændselsindfødningsraten samt ikke-automask regulerede luft- og nitrogenstrømme mv. foretages fra anlæggets flytbare og berøringsfølsomme kontrolpanel. Panelet er venligt doneret af Siemens.

Dataopsamling fra dels PLC-skabet (alle flow-, tryk-, temperatur- og vejecellesignaler) og dels de tilsluttede online gasanalyseinstrumenter sker ved hjælp af Labview.

En forskel i forhold til det helt kontinuerligt fungerende 500 kW anlæg er, at 100 kW anlæggets brændselsindfødningssystem foreløbigt ikke omfatter en slusesilo, hvorfor driften kortvarigt afbrydes under genopfyldning af brændselssiloen. Genopfyldningen initieres og stoppes automatisk baseret på signalet fra brændselssiloophængets vejeceller.

Dosering af vand til anlægget sker fra en slangepumpe, der forsyner dels tre af syv luftlanser i bunden af koksreaktoren og dels den enlige luftlanse i bunden af mellemreaktoren. Slangepumpen reguleres manuelt, men grundet sikkerhedshensyn startes og stoppes den af PLC-en.

Endelig skal det nævnes, at 100 kW anlægget er udført på en måde, så det er let at flytte. Dette er med tanke for gennemførelse af eksterne forsøg på brændsler som spildevandsslam, udsorteret husholdningsaffald og fareklassificeret kødbenmel, men flytbarheden vil også være en fordel, når anlægget snart flyttes fra DTU til Biomasseforgasningsgruppens nye forsøgshal på Risø.

1.5 Hidtidige LT-CFB forsøg

En oversigt over alle hidtidige LT-CFB forsøg, dvs. med alle de tre forsøgsanlæg, der er arbejdet med siden idriftsætning af 50 kW anlægget i 1999, fremgår af tabel 1.

Anlæg Periode	Forsøgsbrændsel	Timer >700 °C og (antal forsøg)	Gasrensning	Bemærkninger
50 KW 1999-2004	Træ Halm (DW95, 1.8 % K 1,2 % Cl) Halm (DW02, 12 % aske) Svinegødning Hønsegødning (kun tørret til 22 % fugt)	2 (1) 82 (mange) 10 (1) 12 (1) 16 (2)	SC (=Sek.Cyklon) SC SC SC SC	Stabile temperaturer Forbedring af C-omsætning mv. Ref. for opskalering
500 kW 2004-2006	Halm (DW02 12 % aske) Svinegødning Svine-biogasrestfibre (44 % aske) Restfibre fra fællesbiogasanlæg	35 (2) 42 (1) 59 (1) 39 (1)	SC SC SC SC&TC(Tert. Cyklon)	650 kW, HHV input ~98 % asketilbageholdelse
100 kW 2009-2010	Halm (2009), kun snittet Halm (2009, piller) Citrus- & tangrestfibre Halm (2010)	5 (2) 67 (3) 37 (2) 52 (1)	SC SC, køler og filter SC, køler og filter SC, køler og filter&POX	Indfødningsproblemer Filtrering ved ~300 °C (over tjæredugpunkt) Nu også Partiel Oxidation

Tabel 1: Oversigt over alle hidtidige LT-CFB forsøg med alle tre LT-CFB anlæg

Den samlede driftstid ved koksreaktortemperaturer over 700 °C, (eksklusive opvarmning og afkøling) er godt 450 timer, hvorunder der i alt er blevet forgasset cirka 35 ton brændsel, hvoraf hovedparten i 500 kW anlægget.

De fleste forsøg er gennemført på groft knuste brændselspiller fremstillet af de varierende brændsler nævnt i den anden kolonne i tabel 1. Til enkelte forsøg er dog benyttet groft formalet (men ikke pelleteret) halm, medens et enkelt 50 kW forsøg blev gennemført på kun delvist termisk tørret gødning fra æglæggende høns.

Der er i alle tilfælde kun benyttet almindelig kvartssand som bed-materiale (ingen additiver) og ofte er efterfølgende forsøg på samme type brændsel gennemført med genpåfyldt bed-materiale fra tidligere forsøg. Dette for at fremme ophobningen af bl.a. K i bed-materialet for således bedre at påvise LT-CFB forgasserens store brændselsfleksibilitet.

1.6 Hidtidige 100 kW LT-CFB forsøg

I tabel 2 er de hidtil gennemførte otte 100 kW forsøg listet enkeltvist og således lidt mere udførligt end i tabel 1. Det fremgår, at der har været tale om i alt cirka 160 driftstimer (ved >700 °C), hvoraf de 36 timer var med delstrømsgaskøling og -posefiltrering. I det sidste, her rapporterede forsøg, blev det kortvarigt forsøgt at reformere den filtrerede gas ved partiel oxidation.

Test nr. og dato	Brændsel	Timer v. >700 °C / timer m. posefilter	Gasrensning	Bemærkninger
1) 28. Maj 2009	Halm, groft formalet	0 / 0	SC (=Sekundær Cyklon)	Indfødningsproblemer
2) 24.-25. juni 2009	Halm, groft formalet	4,5 / 0	SC	Last begrænset til ca. 80 % af indfødningsproblemer
3) 8.-9. juli 2009	Halm, knuste piller	22 / 0	SC	Første lange og stabile forsøg med 100 kW anlægget
4) 8.-9. sep 2009	Halm, knuste piller	17 / 1	SC, køler og posefilter	Første korte forsøg med delstrøms-gaskøler og posefilter. Nye indfødningsproblemer løst.
5) 23.-24. sep 2009	Halm, knuste piller	28 / 6	SC, køler og posefilter	Stabil og effektiv forgasning af halm samt første længerevarende forsøg med gaskøling og posefiltrering.
6) 17.-18. nov 2009	Restfibre fra citrusskaller og tang.	25 / 7	SC, køler og posefilter	Op til > 110 % last ved højeffektivitet. Gaskøling og posefiltrering igen succesfuldt
7) 15.-16. dec 2009	Restfibre fra citrus-skaller og tang. Knuste piller	12 / 6	SC, køler og posefilter	Læk fra primær cyklon dag 1 Dag 2 medførte en fejl i PLC-programmet både opstartsproblemer og en tilstopning nær gasfaklen.
8) 13.-15. jan 2010	Halm, knuste piller	52 /16	SC, køler, posefilter og partiel oxidation	Lang, stabil og effektiv drift på halm. Filterafgangskanal (men ikke køler og filter) tilstoppede på grund af defekt elektrisk varmebændel.

Tabel 2: Oversigt over hidtidige forsøg med 100 kW LT-CFB anlægget

Til de to første 100 kW forsøg blev der forsøgt anvendt groft formalet men ikke pelleteret halm (udtaget før pillepressen), hvilket dog måtte opgives grundet for store indfødningsproblemer, som forhindrede opnåelse af stabil drift i det første forsøg, og som forhindrede opnåelse af mere end cirka 80 % last i det andet.

Under nogle af forsøgene blev der i visse tidsrum også afprøvet en fuldstrøms spraykøler, men denne var bypasset under forsøg 8. Bemærk også, at det herefter rapporterede halmforsøg var det hidtil længste med 100 kW anlægget. Kun et enkelt forsøg med 500 kW anlægget har været længerevarende.

1.7 Formål

Hovedformålet med det her rapporterede forsøg nr. 8 var at gennemføre et langt og stabilt forsøg på halm under driftsbetingelser svarende til de forventelige for det i 2009 projektet evaluerede 6 MW demo-anlæg. Dette som led i en evaluering af demo-anlæggets gennemførlighed og for at kunne sammenligne driften direkte og evaluere opskaleringens indflydelse på driftsdata under sammenlignelige forhold.

Det var også et formål at videreføre de forud indledte aktiviteter vedrørende gaskøling og posefiltrering, ligesom et kort tidligere forberedt forsøg med partiel oxidation af den afkølede og posefiltrerede gas blev gennemført. Som led i karakteriseringen af både gas og aske var formålet endvidere at opnå henholdsvis tjære- og dioxinmålinger.

Det skal bemærkes, at gasrensning blot ved hjælp af en "varm" sekundærcyklon er tænkt inkluderet i 6 MW demoprojektet, men gaskøling og posefiltrering kan vise sig interessant både som en senere forbedring af demo-anlægget og i senere typer af kommercielle LT-CFB anlæg.

2. Konklusion

Forsøgets formål er blevet opfyldt, idet der blev opnået et langt og stabilt forsøg med gode og forventede resultater:

- Undgåelse af askesmelteproblemer trods brugen af alkaliholdig halm og genbrug af bed-materiale fra de tidligere 100 kW LT-CFB halmforsøg, hvor kun almindeligt kvartssand er benyttet som bed-materiale. Hen mod slutningen af forsøget blev processens maksimale bed-temperatur endda øget med cirka 15 °C til godt 760 °C (cirka 10 °C under KCls smeltepunkt!), uden at det førte til driftsforstyrrelser.
- K-koncentrationen i bed-materialet nåede uden deraf følgende driftsforstyrrelser op på 8 %, som er højere end efter alle hidtidige LT-CFB forsøg. Det kan ikke udelukkes, at K-koncentrationen i bed-materialet vil fortsætte med at stige med driftstiden, men det er sandsynligt, at behovet for udskiftning af bed-materialet og/eller tilførsel af additiver vil være minimalt.
- En hensigtsmæssig bed-masse kunne opretholdes uden tilsætning af "friskt" sand. Tilførslen af askepartikler fra brændslet svarede således til summen af tabet af fine bed- og askepartikler gennem forgasserens primærcyklon og de jævnligt udtagne passende store prøver af bed-materialet. Sidstnævnte modsvarer det forventede behov for løbende at dræne en væsentlig del af halmasken fra forgasserens bundudtag, hvilket vil supplere asketilbageholdelsen i sekundærcyklonen og/eller i et eventuelt tilføjet posefilter.
- På basis af en inertmassebalance i en lang og stabil afsluttende del af forsøget blev der i bed-materialet og sekundærcyklonasken opnået en samlet asketilbageholdelse på cirka 98 %, hvilket er på niveau med resultaterne fra det seneste 500 kW forsøg på biogasrestfibre. Denne sammenligning indikerer, at det i hvert fald i dette størrelsesområde er muligt at opnå tilfredsstillende asketilbageholdelser blot ved varm cyklonrensning af rågassen. Ved accept af et øget cyklontryktab forventes det, at 6 MW anlæggets asketilbageholdelse kan fastholdes på næsten samme høje niveau, medens flere parallelle cykloner eller gaskøling og posefiltrering kan vise sig nødvendige ved yderligere markant opskalering.
- Det gennemførte posefilterforsøg blev desværre kun kortvarig grundet en tiltagende tilstopning af gaskanalen efter posefilteret som følge af en defekt elektrisk varmebændel. Især to forudgående 100 kW forsøg på bl.a. halm med gaskøling og posefiltrering over tjæredugpunktet havde dog allerede kraftigt bestyrket denne gasrensningsmetode. Der var således allerede før forsøget en basis for at se gaskøling og posefiltrering som en farbar løsning både i forbindelse med opskalering, og når den rensede LT-CFB gas skal benyttes til formål, der kræver en stort set partikelfri gas.

- Det korte forsøg med partiel oxidation af den posefiltrerede gas bestyrker forventningen om, at den således rensede og reformerede gas også vil kunne anvendes til en række kommercielt interessante formål, der kræver en både aske- og tjærefattig gas.
- Tilfredsstillende (meget) lavt indhold af dioxin i både cyklon- og filteraske blev påvist på basis af askeprøver fra det foregående halmforsøg.
- Ved en gennem mange timer fastholdt indfyret halmmængde på cirka 21 kg/t svarende til en indfyret effekt på 92 kW LHV (cirka 100 kW HHV) var kokstabet mod forsøgets slutning cirka 2,5 % på energibasis.
- For at opnå denne koksomsætning blev der tilført forholdsvis meget vand (godt 10 vægt% af den samlede luft- og vandtilsætning til forgasseren). Ved fastholdt kokstab vil vandforbruget kunne reduceres og/eller lasten vil kunne øges, hvis det - som indikeret - er muligt at indstille lidt højere procestemperaturer. Dertil kommer andre optimeringsmuligheder.
- Omvendt kan et eventuelt ønsket højere koksindhold i asken let opnås ved øgning af lasten og/eller reduktion af vandtilsætningen. Formålet kan være at tilføre jordforbedrende koks til marker, der modtager LT-CFB asken.
- Endelig blev 100 kW anlæggets efterhånden meget automatiserede drift og dataopsamling demonstreret, herunder anlæggets evne til at fortsætte under ren PLC-kontrol ved nedbrud af det pc-baserede system for datavisning og opsamling.

Resultater fra forsøget har dannet grundlag for et paper [Stoholm et al 2010b] og en tilsvarende mundtlig præsentation på den internationale biomassekonference i Lyon, Frankrig i juni 2010. Både hvad angår yderligere publicering og mere overordnede konklusioner, henvises til projektets slutrapport.

På basis af et grundigt designstudie og en lang række dertil knyttede yderligere tekniske og økonomiske vurderinger samt PSO ordningens opbakning, er det besluttet at realisere det tilsigtede 6 MW LT-CFB demoanlæg på Asnæsværket.

3. 100 kW LT-CFB forsøg nr. 8

3.1 Brændsel og bed-materiale

En tidligere fremskaffet portion halmpiller var opbrugt efter 100 kW halmforsøget nr. 5., hvorfor forsøgsbrændslet var tilberedt af en ny portion (2 big bags) halmpiller fra halmpillefabrikken ved Køge.

Forud for indfødningen blev halmpillerne knust i en fodervalse til en maksimal flagetykkelse på cirka 3 mm, hvorved der opnås et produkt, der let lader sig dosere og indføde ved hjælp af 100 kW anlæggets indfødningsudstyr. Det antages, at neddelingsgraden medfører en opvarmningshastighed i pyrolysekammeret nær opvarmningshastigheden for løst oprevet halm, idet de største partikler modsvarer halms indhold af knæ og kærner.

Det var tilstræbt, at den valgte brændselstilberedning, herunder graden af neddeling, var identisk med brændselstilberedningen forud for de fleste tidligere LT-CFB forsøg.

Halmens sammensætning fremgår af bilag 1, hvorfra følgende hoveddata kan nævnes:

Nedre brændværdi, som modtaget	15,82	MJ/kg
Fugtindhold som modtaget	8,3	%
Askeindhold i tørstof	5,9	%
Kaliumindhold i tørstof	1,1	%
Klorindhold i tørstof	0,24	%

Der er altså tale om halm med normalt indhold af aske, kalium og klor.

Som også til de to tidligere LT-CFB forsøgsanlæg er der i alle tilfælde kun benyttet almindelig kvartssand som bed-materiale (ingen additiver), ligesom bed-materialet er blevet genbrugt fra tidligere forsøg på samme brændsel.

Leverandøren Dansand betegner sandet "Støberisand nr. 13". Kornstørrelsesfordelingen og den kemiske analyse fremgår af bilag 2. Her ses at d50 = 125 my, SiO_2 = 93,9 % og K_2O = 1,6 %.

3.2 Forsøgsforberedelser og anlægsforbedringer

Forud for forsøget blev bed-materialet fra de to forudgående forsøg nr. 6 og 7 på restfibre fra CP-Kelco aftappet, hvorefter forgasseren blev inspiceret indvendigt, alle luftdyser tjekket for tilstopninger og lignende.

Derefter blev 114 kg bed-materiale fra det seneste halmforsøg nr. 5 genpåfyldt og suppleret med 15 kg frisk sand (erfaringsmæssigt letter rigeligt med bed-materiale opstarten, ligesom en mindre mængede partikler tabes under opstart).

Efter nævnte knusning af halmpillerne i en fodervalse blev det således tilberedte brændsel stillet ind i forsøgshallen nær påslagget vist i Figur 7. Stop af LT-CFB anlægget, siloopfyldning og genstart efter i 1-2 minutter sker automatisk og nu på en forbedret basis af signalet fra vejeceller i brændselssiloens ophæng. Driftspersonalet skal blot sørge for manuelt at fylde brændsel i påslagget før og når opfyldningssneglen aktiveres.

Figur 7: Automatisk opfyldning af brændselssilo fra manuelt opfyldt påslag

Blandt mange yderligere forsøgsforberedelser skal nævnes:

- Der blev som vanligt fremskaffet en portion demineraliseret vand og tilsluttet et fyldt 200 bar nitrogenbatteri.
- Da driftsforstyrrelser grundet en PLC-programfejl medførte en tilstopning af gasafgangen i slutningen af det forudgående forsøg, blev der gennemført en grundig rensning af gasafgangen samt etableret en tjærefælde under faklen.
- Det fejlbehæftede PLC program blev rettet.
- Posefilterets (enlige) pose blev udskiftet.
- Under nogle af de forudgående forsøg blev der i visse tidsrum også afprøvet en fuldstrøms spraykøler, men denne blev bypasset forud for forsøg 8.
- Den automatisk kontrollerede elektriske opvarmning samt mindre strømme af passiverende nitrogen blev som vanligt startet aftenen før forsøget.

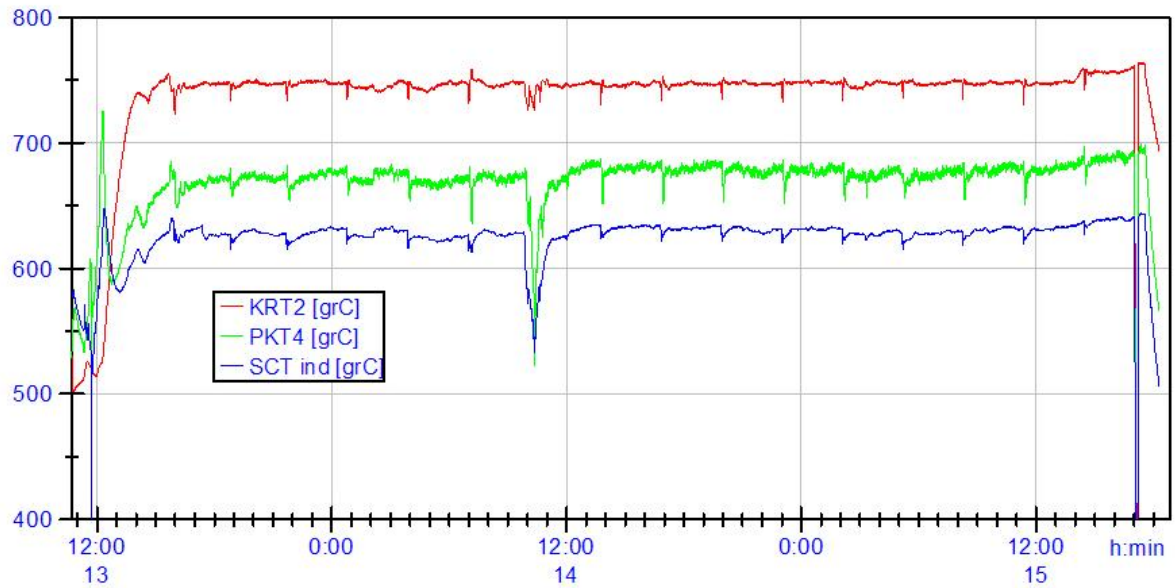
3.3 Forsøgsbeskrivelse

Som det fremgår af temperaturkurverne i Figur 8, blev selve forsøget indledt omkring kl. 11 den 13. januar 2010, hvorefter anlægget var bemandet og i drift frem til kl. 17:40 den 15. januar. De tilbagevendende små temperaturfald skyldes, at anlægget kortvarigt stoppes cirka hver fjerde time for at genopfylde brændselssiloen.

Forsøget blev som vanligt indledt ved tilførsel af først luft og kort derefter også en minimal brændselsstrøm. Brændselsstrømmen blev afbrudt nogle gange og problemer som følge af et utilstrækkeligt renset fakkelrør afhjulpet, men fra kl. 12:15 tilføres en først minimal og senere øget brændselsstrøm kontinuerligt.

Også en fejlagtig afbrydelse af forgasserens varmebændler forsinkede opstarten en smule, men kl. 11:56 indstilles eltilførslen til 100 %. Fra kl. 14:04 var eltilførslen dæmpet til 70 % for således kun at kompensere for forgasserens varmetab til det omgivende rum.

For yderligere at modvirke et temperaturoversving i forlængelse af opvarmningsfasen blev vandtilførsel til koks- og mellemraktor indledt kl. 14:30.



Figur 8: Temperaturer fra det fulde 100 kW LT-CFB forsøg nr. 8 (KRT2, PKT4 og SCT ind er målt i henholdsvis koksreaktoren, pyrolysekammeret og før sekundærcyklonen)

Brændselsstrømmen blev frem imod kl. 14:46 trinvist øget til godt 100 kW (LHV) indfyret. Da "lynudglødning" af en første cyklonaskeprøve viste et glødetab på 36 vægt%, blev brændselsstrømmen dog dæmpet en smule kl. 22:01, hvorefter indfødningsraten de følgende to forsøgsdage var cirka 21 kg/t svarende til 92 kW indfyret effekt, LHV (eller cirka 100 kW (HHV).

Alle luftstrømme blev fra starten ligeledes reguleret manuelt, men den 15. januar kl. 13:30 blev lufttilførslen til koksreaktoren og dermed primært koksreaktortemperaturen reguleret automatisk. Temperatursætpunktet var først cirka 745 °C (som forud manuelt reguleret), men blev kort før forsøgets slutning øget to gange for at kunne vurdere eventuel tendens til agglomerering af bed-materialet.

Undervejs i forløbet blev der som vanligt foretaget såkaldte, og i tidligere forsøgs-rapportering nærmere beskrevne, "lynudglødninger" af sekundærcyklonasken. Dermed kunne man få en indikation af indholdet af uomsat kulstof i asken. Ud fra denne indikation vurderes behovet for tilførsel af demineraliseret vand til koksreaktoren og mellemreaktoren. Tilførslen af vand skete via en omdrejningsreguleret slangepumpe fra en vandtank anbragt på en visuelt aflæst vægt, hvorved vandforbruget kan beregnes.

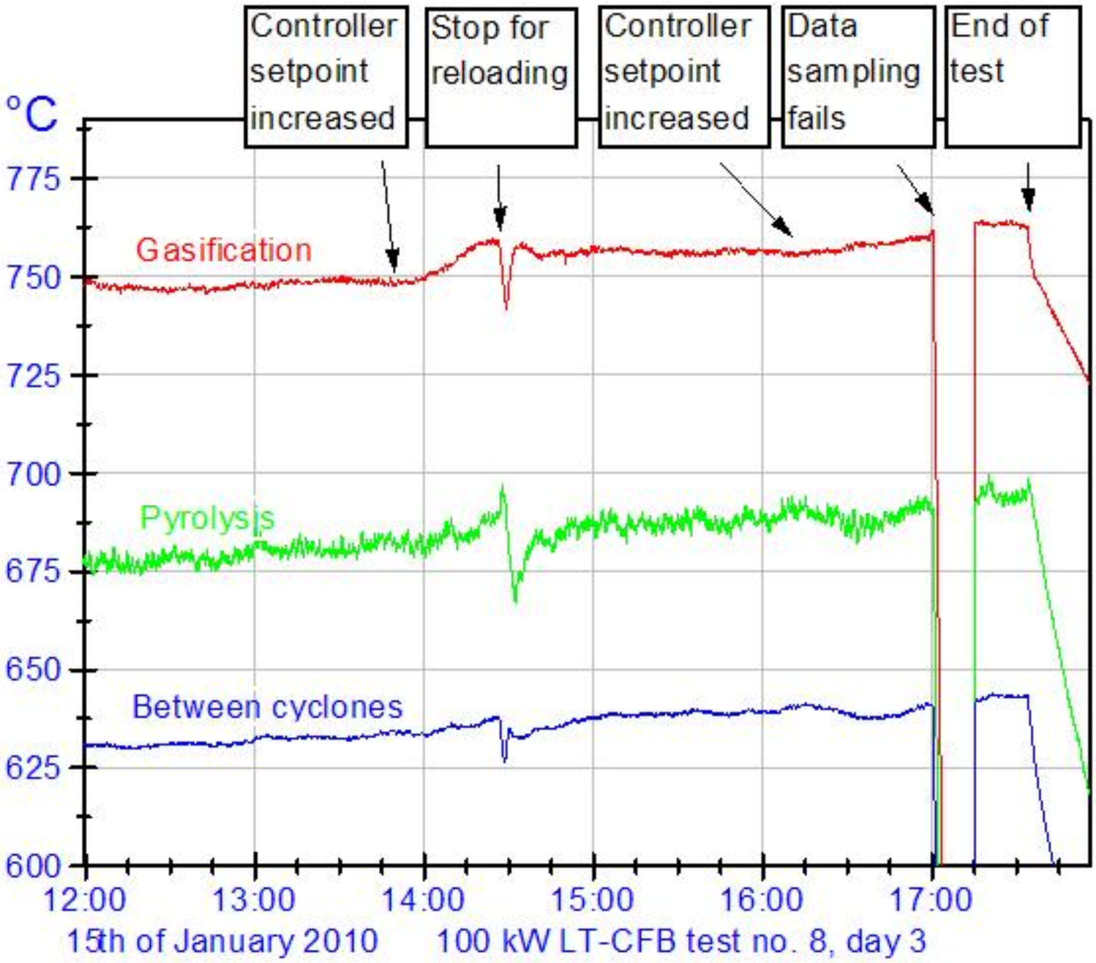
Ovennævnte cyklonaskeprøver, blev, – typisk gennem 5-10 minutter hver anden til tredje. time – tappet fra cyklonfaldrøret over asketønden. Derudover blev der samtidig udtaget prøver af bed-materialet fra et sideudtag, der højdemæssigt er placeret cirka midt i beden i koksreaktoren.

Koksindholdet i bed-materialet bedømmes visuelt, og ellers arkiveres cyklon- og bed-prøverne blot til senere analyse. Dette sammen med en stor brændselsprøve sammenstukket af mange mindre delprøver, der fra påslagget udtages undervejs gennem forsøget.

Efter forsøget er der endvidere udtaget en prøve af den aske, der blev udskilt af posefilteret, men prøven er vurderet til at være påvirket af en stærkt reduceret gasgennemstrømning gennem posefilteret imod forsøgets slutning som følge af en tilstopning af filterafgangsrøret. Tilstopningen var efter alt at dømme en konsekvens af tjærekondensation i filterafgangsrøret som følge af en defekt varmebændel dette sted. Bortset fra lidt brunlig farve nær bunden syntes posen tør og askegrå, hvilket indikerer, at tjærekondensation på posen stort set blev undgået.

3.4 Forsøgsresultater

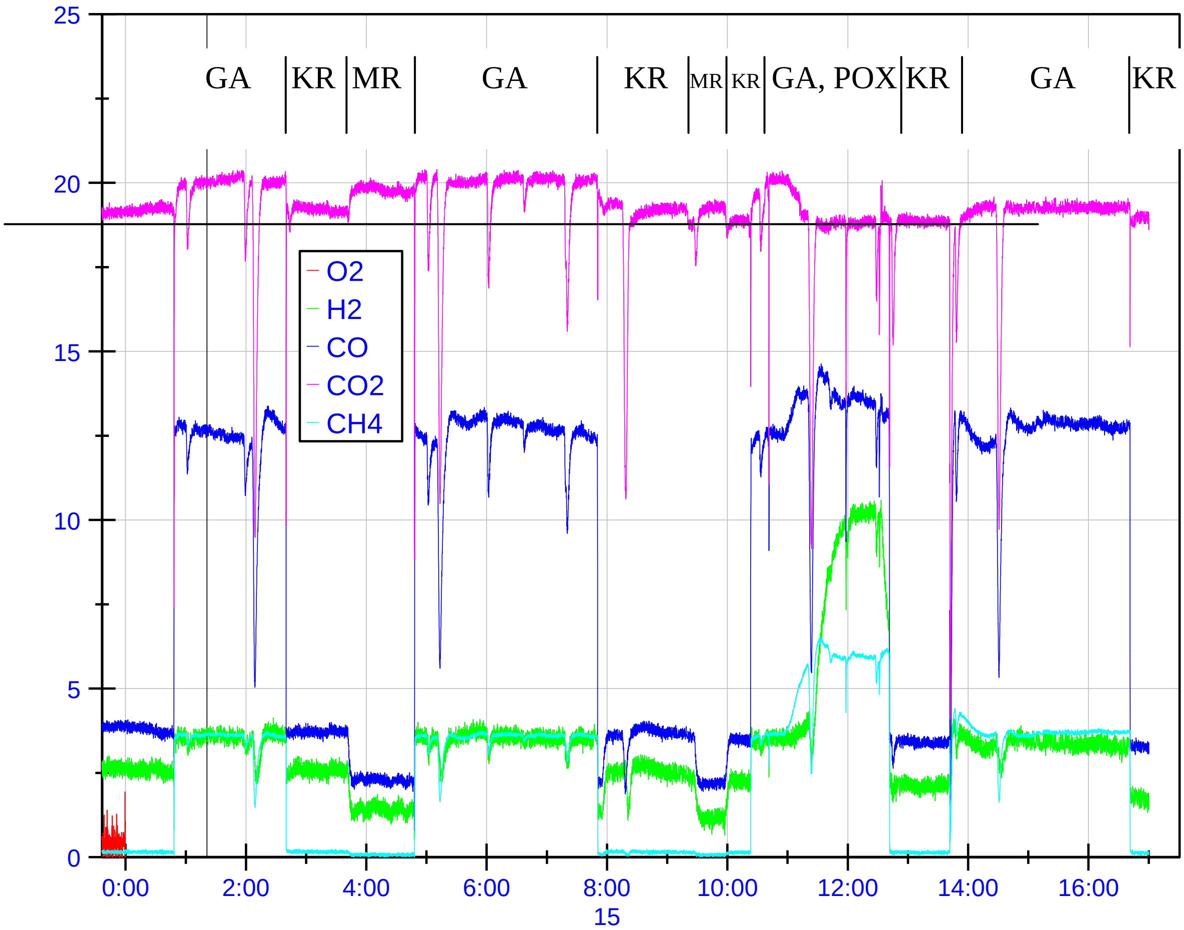
Som det fremgik af Figur 8, blev der opnået en driftstid på cirka 52 timer, hvilket er det hidtil længste med 100 kW anlægget og kun overgået af et enkelt forøg på 59 timer med 500 kW anlægget. I Figur 9 vises de samme temperaturkurver, men der er nu fokuseret på forsøgets sidste (næsten) seks driftstimer.



Figur 9: Temperaturer fra slutningen af 100 kW LT-CFB forsøg nr. 8

Det skal bemærkes, at computernedbruddet ikke påvirkede driften, idet det anlægget blot kørte videre baseret på de forudgående indstillinger. Men bevidstheden om stor ophobning af K i bed-materialet og driftstemperaturer kun cirka 10 °C under KCls smeltepunkt betød, at det var meget spændende at iagttage de tilbagevende visninger af temperatur- og trykmålinger. Der var ingen tegn på agglomereringsproblemer.

De opnåede online gasmålinger fra forsøgets sidste dag, dvs. den 15. januar 2010 fremgår af Figur 10. Som indikeret øverst i figuren, måles der på skift på gas fra koksreaktoren, mellemreaktoren og gasafgangen. Der er tale om en stort set tør gassammensætning, eksklusive N_2, højere kulbrinter end CH_4 og kondenserende tjærestoffer.



Figur 10: Gassammensætning fra KR= Koksreaktor, MR=Mellemreaktor, GA=Gasafgang og POX=aktivering af partiel oxidation (før gasafgang).

Bemærk at der i tidsrummet omkring kl. 12 gennemføres et forsøg med partiel oxidation ("POX"), hvorunder POX-reaktorens temperatur øges fra 300 til 900 °C. Dette medfører et kraftigt forøget indhold af primært H_2 (til godt 10 %) og sekundært CH_4 (til cirka 6 %) i afgangsgassen.

Desværre blev der ikke opsamlet gasmåledata efter pc-nedbruddet kl. 17.
Nærmere resultater i relation til gasrensning og reformering, herunder gassammensætning og tjæreindhold, fremgår af Eranet-rapporten [Zwart et al, 2010].

Efter forsøget blev en brændselsprøve og udvalgte bed- og askeprøver sendt til analyse på/via FORCE Technology's analyselaboratorium, hvorfra udvalgte resultater ses samlet i tabel 3 herunder. Af tabellens første talkolonne fremgår også midelpartikeldiamtre (d50), der i lighed med tilgrundliggende kornstørrelsesfordelinger er bestemt af Anhydros analyselaboratorium.

Bed-/askeprøve	d50 my	Glødetab %,tør	Aske %,tør	K %,tør	Cl %,tør
KR9 d.14/1 kl. 21:20	145	0,6	99,4	6,2	0,18
KR12 d.15/1 kl. 4:55	146	0,7	99,3	6,9	0,24
KR15 d.15/1 kl. 13:27	150	0,7	99,3	6,9	0,26
KR16 d.15/1 kl. 16:33	147	0,6	99,4	8,0	0,34
SC10 d.14/1 kl. 21:20	9,17	31,6	68,4	12	1,9
SC13 d.15/1 kl. 4:55	9,54	29,5	70,5	12	2,0
SC16 d. 15/1 kl 13:27	8,79	30,0	70,0	12	1,8
SC17 d.15/1 kl. 16:33	9,09	30,0	70,0	12	1,9

Tabel 3: Askedata fra 100 kW forsøg nr. 8

Det var endvidere hensigten at analysere askeprøver fra sekundærcyklonen og posefilteret for indhold af dioxin. Grundet tilstopningen af afgangen fra posefilteret blev posefilterprøven imidlertid skønnet uegnet, og det blev besluttet at analysere på askeprøver fra slutningen af 100 kW halmforsøg nr. 5.

I cyklonaskeprøven blev der ikke konstateret indhold af dioxiner over detektionsgrænse-værdierne (I-TEQ (NATO/CCMS) < 2,3 ng/kg), medens resultatet for posefilterprøven (I-TEQ (NATO/CCMS) eksklusive og inklusive detektionsgrænser var henholdsvis 0,72 og 1,1 ng/kg.

For at undgå tvivl om massebalancen for evt. påvist væsentligt dioxinindhold i askeprøverne, blev også brændslet fra forsøg 5 analyseret for dioxin, men med resultater under detektions-grænseværdierne (I-TEQ (NATO/CCMS) < 2,1 ng/kg).

Baseret på brændsels- og cyklonaskeanalyserne samt på øvrige data fra forsøges sidste stabile timer er en række hovedresultater beregnet og præsenteret i tabel 4 herunder.

			Bemærkninger:
Brændselsdata:			
Brændselsflow	kg/h	21	Vurderet på 2 sidste silotømninger
Fugtindhold	%	8,3	
Tør brændsel	kg/h	19,3	
Aske i tør brændsel	%	5,9	
Aske- og vandfrit brændsel	kg/h	18,1	
Tilført aske	kg/h	1,14	
Brændværdi, HHV	MJ/kg	17,2	
Brændværdi, LHV i MJ/kg	MJ/kg	15,8	
Indfyret effekt:			
Indyret effekt, HHV	MW	0,100	
Indyret effekt, LHV	MW	0,092	
Indgående strømme:			
Brændsel	kg/h	21	
Luft i alt	kg/h	28,7	
Vand til KR og MR	kg/h	3,5	Vandpumpe 15 rpm. (14 rpm til sidst)
Ind i alt	kg/h	53,2	
Separeret:			
Udtaget bed-materiale:	kg/h	0,592	8,29 kg fra kl 00 - 14:00
SC aske	kg/h	0,75	Ca. 12 kg i ca. 16 timer frem imod kl godt 16
Filteraske	kg/h	0,12	Fra forsøg 6 og antaget 10 % delstrøm
Separeret i alt	kg/h	1,46	
Ophobet i forgasser:			
Ophobet bed-materiale	kg/h	0	KRP2-KRP8 = ca.65 cmVS fra kl. 00-14 d.15/1
Renset gas til fakkel			
Ind - separeret – ophobet	kg/h	51,7	Beregnet som differens
Gasrensning			Uden kendskab til filteraskestrøm!
Kulstof i udtaget bed-materiale	%	0,60	For KR 16
Kulstof i SC aske	%	30,0	For SC 17, Antages også i filteraske
Asketilbageholdelse i bed og SC	kg/h	1,11	Baseret på kulstoffri aske!
Asketilbageholdelse i bed og SC	%	98,0	Baseret på kulstoffri aske!
SC effektivitet	%	96,5	Baseret på kulstoffri aske!
Støvkoncentration i gas fra SC	g/kg	0,623	Beregnet som inert differens + kulstof!
PC tryktab	mmVS	80	d.15/1 KL 16 til 17
SC tryktab	mmVS	130	d.15/1 KL 16 til 17
D_50, SC aske	my	9	SC-askeprøver fra 14/1 kl 21:20 til 15/1 kl 16:33

Tabel 4: Hoveddata fra 100 kW forsøg nr. 8 på valsede halmpiller fra Køge primo 2010 (data er fra forsøgets sidste timer, dog eksklusive tiden med den afsluttende temperaturstigning)

En lang række yderligere data, herunder tryk- og temperaturmålinger samt resultater af ”lynudglødninger”, er opnået, hvorudfra forsøget senere vil kunne evalueres nærmere.

3.5 Diskussion

Forsøget bestyrkede resultaterne fra tidligere forsøg for så vidt angår muligheden for særdeles præcist at kontrollere procesbetingelserne og herunder reaktorkamrenes temperaturer på det tilsigtede niveau.

Også under dette lange forsøg kunne agglomereringsproblemer udgås, trods en række problematiske forudsætninger:

- Brugen af alkaliholdig halm
- Brugen af almindeligt kvartssand uden additiver som bed-materiale
- Genpåfyldningen af bed-materiale fra forudgående halmforsøg
- Muligheden for irreversibel agglomerering under stoppene for brændselspåfyldning
- Bed-temperaturer på cirka 745 °C og øgningen til godt 760 °C mod forsøgets afslutning.

Som det fremgår af tabel 3, voksede indholdet af K i bed-materialet mod forsøgets afslutning til cirka 8 %, hvilket er det hidtil højeste for alle LT-CFB forgasningsforsøg. Indholdet af K i cyklonasken var derimod konstant gennem forsøgets sidste mange timer og niveauet (12 %) afveg ikke væsentligt i forhold til tidligere halmforsøg.

Baseret på det ovennævnte er der grund til at formode, at forsøget uden problemer kunne have været gennemført med 5-10 °C højere bed-temperaturer i koks- og mellemreaktorerne. Derved ville kokstabet kunne reduceres yderligere, og/eller mindre vandtilsætning havde været nødvendig. Det er dog også muligt, at en forlængelse af forsøget ville medføre et endnu højere K-indhold i bed-materialet, som ville kunne forhindre en sådan optimering. I givet fald vil man kunne vælge en løbende udskiftning af bed-materialet og/eller tilførsel af agglomereringshæmmende additiver.

Ophobningen af K i bed-materialet harmonerer med, at der løbende skulle aftappes bed-materiale for at fastholde bed-højden i koksreaktoren på det ønskede niveau. Tilførslen af askepartikler fra brændslet svarede således til summen af tabet af fine bed- og askepartikler gennem forgasserens primærcyklon og de jævnligt udtagne passende store prøver af bed-materialet.

Så længe bed'ens kornstørrelsesfordeling forbliver hensigtsmæssig og den øgede K-koncentration ikke giver problemer, er askeophobningen positiv i den forstand, at der ikke er behov for tilførsel af friskt sand for at opretholde forgasserens optimale indhold af bed-materiale og fordi askeophobningen supplerer sekundærcyklonens asketilbageholdelse. Set i lyset af sekundærcyklonens meget høje beregnede effektivitet (96,5 %, antaget kulstoffri aske) og det forhold, at den i bed'en tilbageholdte aske har form af forholdsvis grove partikler, som cyklonen endnu mere effektivt ville udskille, er asketilbageholdelsen i bed'en næppe afgørende for at opnå en høj samlet asketilbageholdelse.

Behovet for løbende at udtage en betydelig del af halmasken fra forgasseren bund bekræfter tendensen fra tidligere LT-CFB forsøg på både halm og andre brændsler.

Vurderet på basis af en inertmassebalance for forsøgets sidste 15 timer blev der i bed-materialet og sekundærcyklonasken opnået en samlet asketilbageholdelse på 98 %, hvilket er på niveau med resultaterne fra det seneste 500 kW forsøg på biogasrestfibre. I dette brede størrelsesområde har det altså været muligt at opnå tilfredsstillende asketilbageholdelser blot ved varm cyklonrensning af rågassen. Ved accept af et øget cyklontryktab forventes det, at 6 MW anlæggets asketilbageholdelse kan fastholdes på næsten samme høje niveau, medens flere parallelle cykloner eller gaskøling og filtrering kan vise sig nødvendige ved yderligere markant opskalering.

Posefilterforsøget i forsøg 8 blev desværre væsentligt mindre varigt end selve forgasningsforsøget på grund af en tiltagende tilstopning af gaskanalen lige efter posefilteret. Årsagen var dog blot en defekt elektrisk varmebændel. To forudgående 100 kW forsøg (på bl.a. halm) med gaskøling og posefiltrering over tjæredugpunktet havde allerede bestyrket dette perspektivrige gasrensningskoncept. Der var således allerede før forsøget basis for at se gaskøling og posefiltrering som en farbar løsning både i forbindelse med opskalering, og når den rensede LT-CFB gas skal benyttes til formål, der kræver en stort set partikelfri gas.

Af Figur 10 fremgår det i tidsrummet omkring kl. 12, at lufttilsætningen til POX-kammeret og den deraf følgende temperaturstigning til 900 °C medfører et kraftigt forøget indhold af primært H_2 (stiger til godt 10 %) og sekundært CH_4 (stiger til cirka 6 %) i afgangsgassen. Trods tilførslen af luft opnås disse koncentrationsstigninger, uden at der opstår et tilsvarende øget indhold af CO_2. Tværtimod falder CO_2/CO forholdet mærkbart.

Det korte forsøg med partiel oxidation af den posefiltrerede gas bestyrker således forventningen om, at den filtrerede og derefter reformerede gas også vil kunne anvendes til en række kommercielt interessante formål, der kræver en både aske- og tjærefattig gas.

Yderligere resultater af både gennemførte tjæremålinger og POX-forsøget fremgår af [Zwart et al, 2010].

Der er også opnået analysedata vedrørende tungmetaller, som rapporteres af det forudgående PSO-2007 projekt [Stoholm et al 2010a].

PAH indholdet i cyklon- og filteraske blev ikke bestemt for dette forsøg, men det er efter flere tidligere LT-CFB forsøg konstateret, at PAH indholdet ikke er til hinder for direkte udspredning på landbrugsjord. Den primære årsag er formentlig, at der – grundet lav temperatur og opholdstid – kun sker en beskeden krakning af de primært udviklede lette tjærestoffer i pyrolysekammeret.

Fra halmforsøg nr. 5 havde kun filterasken et indhold a dioxiner over de for disse særligt fine partikler reducerede detektionsgrænser. Niveauet er dog meget lavt og således uproblematisk. Der kan dog være grund til at være opmærksom på muligheden for dannelse af dioxin i posefiltre ved afvigende brændselssammensætning og ved afvigende procesbetingelser, herunder ved valg af højere posefiltertemperatur.

Ved en gennem mange timer fastholdt indfyret halmmængde på cirka 21 kg/t, svarende til en indfyret effekt på 92 kW LHV (cirka 100 kW HHV), var kokstabet gennem forsøgets sidste 15 timer cirka 2,5 % på energibasis. I denne vurdering indgår ikke den sidste times drift med 10-15 °C højere temperatur i koksreaktoren, der formentlig har medført en øget kulstofomsætning. Dette kan imidlertid ikke underbygges med forsøgsdata, fordi den sidste cyklonaskeprøve viste sig at være uanvendelig, og den er derfor ikke analyseret.

Det skal nævnes, at en øgning af den indfyrede effekt til 100 kW (LHV) formentlig som minimum ville ophæve den positive virkning af den øgede temperatur.

For at opnå den konstaterede høje koksomsætning, blev der tilført mere vand end ønskeligt (godt 10 % vægt% af den samlede luft- og vandtilsætning). Hvis forsøget var fortsat ved de til slut indstillede højere temperaturer, må det dog antages, at vandtilsætningen ville kunne reduceres for fastholdt indfyret effekt og kokstab. I givet fald opnås fordele i form af reduceret gasvolumenstrøm, forbedret gaskvalitet og reduceret røggastab.

Forsøget styrker tidligere konklusioner i retning af, at halm er forholdsvis ”trægt” at forgasse i forhold til brændsler, som separerede restfibre fra gylle og biogasanlæg. Hvor den indfyrede effekt på sådanne brændsler typisk kan øges ud over LT-CFB forgasseren nominelle effekt, bør der påregnes en mindre reduktion, hvis effektiv koksomsætning ønskes på halm. Ved at reducere den indfyrede effekt reduceres den mekaniske nedbrydning af koks til fint støv, der kan tabes gennem primærcyklonen, og der opnås bedre forudsætninger (koks- og gasopholdstid) for især de langsomme endoterme koksforgasningsreaktioner på basis af CO_2 og vanddamp.

”Omvendt” kan et eventuelt ønske om markant højere koksindhold i asken let opfyldes ved at reducere vandtilsætningen og/eller øge brændselsindfødningen. Formålet kan være at tilføre jordforbedrende koks til marker, der modtager LT-CFB asken samt langtidsdeponering af kulstof i dyrkningslagt.

Endelig blev 100 kW anlæggets efterhånden meget automatiserede drifts- og dataopsamling demonstreret, herunder anlæggets evne til at fortsætte under ren PLC-kontrol ved nedbrud af det pc-baserede system for datavisning og -opsamling.

Den forud for forsøget forberedte PLC-baserede regulering af koksreaktortemperaturen blev aktiveret sidst i forsøget, og reguleringsparametrene tunet, hvorefter temperaturreguleringen fungerede upåklageligt.

Den ligeledes forberedte automatiske regulering af sandstanden i L-benet blev også aktiveret, men hensigtsmæssig sandstand indstillede sig ved reguleringsventilens minimalt indstillelige luftstrøm. Ved øgning af luftstrømmen til L-benet var det dog tydeligvis muligt at påvirke sandstanden i nedadgående retning, hvorfor det må antages, at reguleringen vil kunne etableres senere, herunder også på 6 MW anlægget.

4. Formidling

Resultater fra forsøget har dannet grundlag for et paper [Stoholm et al 2010b] og en tilsvarende mundtlig præsentation på den internationale biomassekonference i Lyon, Frankrig i juni 2010. For information om projektets yderligere publicering henvises til projektets hovedrapport.

5. Referenceliste

Stoholm et al 2010a. LT-CFB forgasser, videreudvikling og kommercialisering, Slutrapport for PSO-ForskEl projektnummer 2007-7504.

Stoholm et al 2010b, The Low Temperature CFB gasifier – 100 kWth tests on straw and new 6 MWth demonstration plant. Paper submitted for the International Biomass Conference, Lyon, France June 2010.

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Stoholm, 1998. EPO patentansøgning nr. 98 958 839.7-2104.

Zwart et al, 2010. Tar removal from low-temperature gasifiers. Slutrapport for PSO-Eranet projektnummer 2008-1-10036.

6. Bilagsoversigt

Bilag 1: Brændselsanalyse fra FORCE Technology

Bilag 2: Sandanalyse, sammensætning og kornstørrelsesfordeling (fra: http://www.dansand.dk/fileadmin/download/dansk/st%C3%B8ber_13.pdf)

DANAK
TEST Reg.nr. 65

FORCE TECHNOLOGY

Rekvirent :

LT_CFB

Att.: JCR

Journal nr.: U10-86

2010.02.15

PRØVNINGSRAPPORT

Undersøgelse af fast brændsel

Sag. nr.	:	108-28508-11
Rekvisitions nr.	:	-
Prøve modtaget d.	:	2010.01.20
Prøvningstermin	:	2010.01.20 – 2010.02.12

Resultaterne for prøvningen findes på side: 2 – 3 og bilag 1 (XRF analyse)

Præcision og usikkerhed jvf. vedlagte bilag.

FORCE Technology

Susanne Westborg
Specialist

Kemisk Analyse

Rene Hansen
Tekniker

Kemisk Analyse

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FORCE TECHNOLOGY

Rekvirent :

LT-CFB

Journal nr.: U10-86

Undersøgelse af fast brændsel				
Prøve af	Halmpiller			
Mærket	LT_CFB 100kW. Forsøg 8. Halm fra Køge, 13-15/01-2010.			
Prøvens størrelse	720,2 g	Emballage	Tæt plast pose	
Forbehandling af prøve:			I henhold til CEN/TS 14780	

Analyse af brændslet		Basis:	Vand- og askefri prøve	Vandfri prøve	Indleveret prøve
Vand, totalt		CEN/TS 14774-1	-	-	8,3 %
Aske		CEN/TS 14775	-	5,9 %	5,4 %
Flygtige bestanddele		CEN/TS 15148	81,3 %	76,5 %	70,2 %
Svovl	S	prCEN/TS 15289	///	0,11 %	0,10 %
Hydrogen	H	CEN/TS 15104 (Vario El)	///	5,8 %	5,4 %
Carbon	C	CEN/TS 15104 (Vario El)	///	47,5 %	43,6 %
Nitrogen	N	CEN/TS 15104 (Vario El)	///	0,65 %	0,60 %
Oxygen	O	Calculated cf. CEN/TS 15296	///	40,0 %	36,7 %
Chlor	Cl	prCEN/TS 15289	///	/// %	/// %
Chlorid	Cl^-	CEN/TS 15105	///	/// %	/// %

Brændslets fysiske egenskaber								
Øvre brændværdi	CEN/TS 14918, indleveret prøve	4,78	kWh/kg~	4106	kcal/kg~	17,20	MJ/kg
Effektiv brændværdi,	beregnet på indleveret prøve	4,40	kWh/kg~	3780	kcal/kg~	15,82	MJ/kg
Effektiv brændværdi,	beregnet på vandfri prøve	4,85	kWh/kg~	4174	kcal/kg~	17,47	MJ/kg
Effektiv brændværdi,	bereg. på vand- og askefri prøve	5,16	kWh/kg~	4434	kcal/kg~	18,56	MJ/kg

Askens smelteforløb	CEN/TS 15370-1	Bestemt i:	Reducerende atm.	Prøveform: Cylinder	
	Blødgørings	temperatur	(DT)	///	°C
	Halvkugle	temperatur	(HT)	///	°C
	Flyde	temperatur	(FT)	///	°C

Bemærkninger:

Resultaterne for ED-XRF screeningsanalysen findes i bilag 1. De her anførte resultater er på tør basis.

///:Ikke analyseret parameter.

Rekvirent :

LT_CFB

Journal nr.: U10-86

Undersøgelse af fast brændsel						
Prøve af	Halmpiller					
Mærket	LT_CFB 100kW. Forsøg 8. Halm fra Køge, 13-15/01-2010.					
Prøvens størrelse		720,2 g	Emballage	Tæt plast pose		
Forbehandling af prøve:				I henhold til CEN/TS 14780		
Indhold af sporelementer (Minor elements) *						
			Basis:			Tør prøve
Arsen	As	(1)			//	mg/kg
Cadmium	Cd	(1)			0,13	mg/kg
Kobolt	Co	(1)			//	mg/kg
Chrom	Cr	(1)			//	mg/kg
Kobber	Cu	(1)			3,0	mg/kg
Kviksølv	Hg	(1)			//	mg/kg
Mangan	Mn	(1)			//	mg/kg
Molybdæn	Mo	(1)			//	mg/kg
Nikkel	Ni	(1)			1,3	mg/kg
Bly	Pb	(1)			//	mg/kg
Antimon	Sb	(1)			//	mg/kg
Vanadin	V	(1)			//	mg/kg
Zink	Zn	(1)			//	mg/kg

Metoder:

(1) CEN/TS 15297 (total oplukning med $H_2O_2/HNO_3/HF$ og ICP-MS analyse)

Bemærkninger:

* : Ikke akkrediteret prøvning

//: Ikke analyseret parameter.

XRF Analyse - XLAB 2000

BILAG 1

Journal nr.: U10-86.

Prøveidentifikation:	x5222	Fortyndingsmiddel:	None
Beskrivelse:	Biomasse	Prøvevægt (g):	4,006
Metode:	Biofuel3	Fort. middel vægt(g)	0
Sags Id.:	1001 januar 2010	Fortyndingsfaktor	1
Prøveform:	Pressed tablet, 32 mm	Prøverotation:	No
Prøvetype:	Preßtablette	Dato for optagelse:	26-jan-10
Prøve status:	AAAXXX	Dato for beregning:	26-jan-10

Resultater

Z	Symbol	Element	Conc.	
11	Na	Sodium	*<0,2 %*	
12	Mg	Magnesium	*0,14 %*	
13	Al	Aluminum	*0,046 %*	
14	Si	Silicon	*3,3 %*	
15	P	Phosphorus	*0,10 %*	
16	S	Sulfur	*0,11 %*	
17	Cl	Chlorine	*0,24 %*	
19	K	Potassium	*1,1 %*	
20	Ca	Calcium	*0,52 %*	
22	Ti	Titanium	*0,002 %*	
23	V	Vanadium	*<0,002 %*	
24	Cr	Chromium	*<0,0005 %*	
25	Mn	Manganese	*0,004 %*	
26	Fe	Iron	*0,018 %*	
27	Co	Cobalt	*<3 µg/g*	
28	Ni	Nickel	*2 µg/g*	
29	Cu	Copper	*2 µg/g*	
30	Zn	Zinc	*10 µg/g*	
33	As	Arsenic	*<1 µg/g*	
42	Mo	Molybdenum	*<1 µg/g*	
48	Cd	Cadmium	*1 µg/g*	
56	Ba	Barium	*30 µg/g*	
82	Pb	Lead	*<5 µg/g*	

Bemærkning: siliciumværdien er over kalibreringsområdet.

Dato: 26-01-2010

Sagsbehandler

FORCE TECHNOLOGY

STANDARDBILAG
FASTE BIOBRÆNDSLER
Usikkerhed for anvendte metoder

Parameter	**Metode**	**Repeterbarhedsgrænse, r**	**Reproducerbarhedsgrænse, R**
Vand, totalt	CEN/TS 14774-1	< 10 % vand: 0,5 % w/w > 10 % vand: 5 % af gn.snit	*Kan ikke angives p.g.a der ikke foreligger tilstrækkelig dokumentation*
Vand, analyseprøve	CEN/TS 14774-3	0,2 % w/w	*Kan ikke angives p.g.a der ikke foreligger tilstrækkelig dokumentation*
Aske	CEN/TS 14775	0,2 % w/w	0,4 % w/w
Svovl (S)	prCEN/TS 15289	< 0,05 % S: 0,005 % w/w > 0,05 % S: 10 % af gn. snit	< 0,05 % S: 0,01 % w/w > 0,05% S: 20 % af gn.snit
Flygtige bestanddele	CEN/TS 15148	3 % af gn.snit	4 % af gn.snit
Carbon (C)	CEN/TS 15104	0,5 % w/w	1,5 % w/w
Hydrogen (H)	CEN/TS 15104	0,25 % w/w	0,5 % w/w
Nitrogen (N)	CEN/TS 15104	< 0,5 % N: 0,05 % w/w > 0,5 % N: 10 % af g.snit	< 0,05 % N: 0,1 % w/w > 0,05 % N: 20 % af g.snit
Chlor (Cl)	prCEN/TS 15289	< 0,05 % Cl: 0,005 % w/w > 0,05 % Cl: 10 % af gn. snit	< 0,05 % Cl: 0,01 % w/w > 0,05 % Cl: 20 % af gn.snit
Chlorid (Cl^-)	CEN/TS 15105	< 0,05 % Cl^-: 0,005 % w/w > 0,05 % Cl^-: 10 % af gn. snit	< 0,05 % Cl^-: 0,01 % w/w > 0,05 % Cl^-: 20 % af gn.snit
Brændværdi	CEN/TS 14918	120 J/g	300 J/g
Askens smelteforløb	CEN/TS 15370-1	30 °C	*Kan ikke angives p.g.a der ikke foreligger tilstrækkelig dokumentation*

% w/w:	*Vægtprocent*
Repeterbarhedsgrænse, r:	*Angiver den maksimale afvigelse ved en dobbeltbestemmelse udført af den samme person med samme udstyr på den samme prøve indenfor et kort tidsrum.*
Reproducerbarhedsgrænse, R:	*Angiver den maksimale afvigelse for gennemsnittet af dobbeltbestemmelser foretaget på to forskellige laboratorier på repræsentative delprøver af den samme prøve.*

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SIGTEANALYSE

Udskrevet: 19-03-2009

Vare nr.: 13 | Varebetegnelse: Sand 13 | Periode: 01-02-2009 - 10-03-2009

Maskeåbning, mm	Sandmængde på sigte		Sandmængde gennem sigte	Beregning af middelkornstørrelse	
Din/Iso 13	g	%	Aktuel, %	Faktor	Værdi
2,000	0,00	0,0	100,0	2,366	0,0
1,400	0,00	0,0	100,0	1,673	0,0
1,000	0,00	0,0	100,0	1,183	0,0
0,710	0,00	0,0	100,0	0,843	0,0
0,500	0,00	0,0	100,0	0,596	0,0
0,355	1,30	1,3	98,7	0,421	0,5
0,250	1,64	1,6	97,1	0,298	0,5
0,180	12,54	12,5	84,5	0,212	2,7
0,125	32,18	32,2	52,3	0,150	4,8
0,090	24,40	24,4	27,9	0,106	2,6
0,063	10,78	10,8	17,2	0,075	0,8
0,000	17,16	17,2	0,0	0,035	0,6
Sum	100,00	100,0			12,5

Middelkornstørrelse, mm: 0,125 | Teoretisk kornoverflade, cm2/g: 239 | American Fineness No.: 128

Gleichmäßigkeitsgrad (GG): 52

Massefylde, kg/m3: 2564 | Rumvægt, g/cm3: 1,292 | Glødetab, %: 0,47 | Sintringstemp., °C: 1200

SiO_2, %:	93,870	Al_2O_3, %:	2,950	CaO, %:	0,030	Na_2O, %:	0,280
K_2O, %:	1,600	Fe_2O_3, %:	0,450	TiO_2, %:	0,640