Quality Characteristics of Biofuel Pellets

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1.   Introduction

By Lars Nikolaisen, Danish Technological Institute

This project was accomplished by six partners, five in Denmark and one in the United States. The partners are qualified in various fields of combustion and biomass technology. All of them have contributed to this report. The partners are:

Danish Technological Institute	Project management, small-scale combustion tests and economy
dk-TEKNIK ENERGI & MILJØ	Fuel and ash analyses, compositions of pellet mixtures
Biotechnological Institute	Test production of pellets
Tech-wise	Test of biofuels under simulated power plant conditions
Brigham Young University, USA	Test of biofuels under simulated power plant conditions
Sprout-Matador A/S	Pellets production technology

The project is financed by the Danish Energy Agency, by ELTRAs PSO funding and by the project partners.

The project is reported in two steps:

1. This final report includes a description of the first activities at Brigham Young University (BYU) and a description of all activities carried out by the Danish partners.

2. All activities at BYU will be reported in the final PSO report.

1.1. Summary

It is the aim of this project to document the technical and economic potential of biofuel pellets produced from mixtures of various biomass waste products (from forestry and farming), added binding agents and anti-slagging additives. Imported biofuels may also be included. A mixture of 100,000 tons of biofuel of good quality, e.g. wood waste, and 200,000 tons of biofuel of inferior quality, e.g. grain screenings, straw or shea nut shells, may result in 300,000 tons of pellets with known characteristics. This procedure makes it possible to exploit a type of biomass that would otherwise be unfit for energy purposes. I.e. 1 ton of wood waste acts as a catalyst in a process that allows application of 2 tons of another type of biomass of inferior quality for energy purposes.

The main activities of the project are:

Literature study and development of recipes

Literature was studied in order to determine the extent of the international research within analysis and combustion test of biofuels with additives (binding agents and anti-slagging additives). The result is a list of relevant binding agents and anti-slagging additives, which are expected to be suitable for firing in small- and large-scale boilers (district heating and utility boilers).

For small boilers the most important requirement as to fuel quality is that the ash is smooth and fine like powder without any slagging formations. For utility boilers, the demand is more complex, among other things the chemical composition of the ash formations on the heat surface is important due to high temperature corrosion.

The development of recipes during the project was an iterative process during which a few recipes were produced and tested, and conclusions were made before the next recipes were decided.

Recipes	Pellet diameter	Biofuel 1	Biofuel 2	Anti-slagging additive	Binding agent	Lubricant
Wood pellets	8 mm	1/1 sawdust				
R1	12 mm	1/1 straw		1% aluminium hydroxide		
R2	12 mm	1/1 straw		2% kaolinite		
R3	12 mm	1/1 straw		1% calcium oxide	3% molasses	
R4	12 mm	1/3 sawdust	2/3 straw	5% limestone		
R5	12 mm	1/3 sawdust	2/3 straw	5% aluminium hydroxide	5% molasses	
R6	12 mm	1/3 sawdust	2/3 straw	5% limestone	5% molasses	5% rapeoil
R7	12 mm	1/3 sawdust	2/3 grain screenings	5% limestone	5% molasses	3% rapeoil
R8	12 mm	1/3 sunflower shells	2/3 grain screenings	5% limestone	5% molasses	2% rapeoil
R9	12 mm	1/3 shea nut shells	2/3 grain screenings	5% limestone	5% molasses	2% rape oil
R10	12 mm	1/1 grain screenings		5% limestone	5% molasses	2% rape oil
R11	12 mm	1/3 sawdust	2/3 grain screenings	3% limestone	2% molasses	2% rape oil
R12	12 mm	1/3 shea nut shells	2/3 grain screenings	3% limestone		

Table 1-1. The 12 recipes developed in the project. Wood pellet is reference.

Test production

12 samples of 700 kg were mixed and pelletized from a variety of biofuels added binding agents and anti-slagging additives (see Table 1-1). The hardness and formation of fines in the pellets were determined. The production of the 12 pellet mixtures was carried out at the Biotechnological Institute's pilot plant in Sdr. Stenderup. It was necessary to use 1,500 kg of mixtures for each recipe since 700 kg was required for combustion tests at Danish Technological Institute and approx. 100 kg for other purposes such as tests at Brigham Young University (BYU). The remaining quantity of 600-700 kg is essential for determining the best possible operational conditions during the pellet production.

Pellet market and economy

During the last 10 years, the Danish wood pellet market has been very turbulent: From a consumption of 0 in 1980 to 300,000 tons/year in 2001. The consumers are district heating plants, industries, public buildings, private households and - from 2003 - utility companies. The rapidly growing demand has challenged the pellet manufacturers

regarding access to raw materials, production capacity, storage facilities and distribution systems. Pellet shortage has lead to import from the Baltic countries and overseas, and the pellet price has increased.

The biofuel pellets developed in this project point in a new direction: By mixing different raw materials and additives, it is possible to develop a pellet with well-defined characteristics such as:

- No slagging tendency (except at air nozzles)
- High ash content (like coal)
- Some dust fouling on heat surfaces
- Price competitive to wood pellets

The production price of most of the 12 recipes is competitive to the calculated production price of wood pellets. Note that this is a test production which means that expensive raw materials such as rapeoil were used in some tests. If rapeoil is omitted, the price will be about 100 DKK/tons lower. The calculation shows that it is possible to develop useful biofuel pellets out of waste materials. In general, the price settings, investments, depreciation, etc. are conservative in this calculation. This means that a more detailed calculation for commercial production would generally result in lower prices.

Combustion test 1

The 12 samples were test fired for 3 days in a 30 kW grate-fired boiler. Emissions and output were measured and the combustion was evaluated. The test method was applied in two previous projects during which pure non-mixed biofuels without binding agents or anti-slagging additives were tested. This ensures comparability with previous tests. The combustion tests were carried out at a test rig in the Energy Laboratory at Danish Technological Institute in Aarhus, Denmark.

The main impressions of the combustion tests are as follows:

Wood pellets
No problems. Constantly a very good combustion, steady heat output and flue gas temperature. No slag, neither fixed in the combustion chamber, nor in the ash. No considerable fouling in combustion chamber and flue gas tubes. The pellet quality was high, i.e. the pellets did not emit dust when filled into the fuel hopper.

R6, R7, R8, R11 and R12
No problems with slag in the ash (except R12), but a considerable formation of fixed slag at the air nozzles. The pellet quality was high, i.e. the pellets did not emit dust when filled into the fuel hopper. The high quality also had a positive effect on the combustion quality. The combustion chamber and flue gas tubes were heavily fouled.

The fuels are probably useful in most small boilers, but using them will require a lot of work regarding frequent cleaning of combustion chamber and flue gas tubes.

R9 and R10
Like R6, R7, R8, R11 and R12 except from some tendency of slag in the ash. It did not cause problems in the current boiler because the slag was crumbly, but it might cause problems in less robust and simpler boilers. There was serious formation of fixed slag at the air nozzles.

R4 and R5
No problems regarding slag in the ash, but a serious formation of fixed slag at the air nozzles. Furthermore, combustion chamber and flue gas tubes were very heavily fouled. The pellets emitted a lot of dust when filled into the fuel hopper due to the poor pellet quality.

R1, R2 and R3
All the tests were stopped during the first two days due to huge slag problems - the combustion chamber was completely filled with slag. The combustion chamber and flue gas tubes were very heavily fouled and the pellet quality was poor.

Analyses

All raw materials were analysed in detail using standard methods (moisture, ash, C, H, O, N, S, calorific value) and CCSEM (main elements of the ash). The compositions of produced pellets were calculated from the recipes. The advantage of this method was that suggested recipes could be evaluated before the eventual production, and that the analysis costs were reduced. A spreadsheet workbook was elaborated for the calculations, including calculation of various indices to evaluate the suggested recipes.

2-3 kg samples of each of the 12 mixtures produced were milled and ashed in the laboratory at 550 °C. The melting behaviour of the ashes was studied using the "MAF" method (melt area fraction), developed at dk-TEKNIK (Hjuler, K. "Ash Fusibility Detection Using Image Analysis". In "Impact of Mineral Impurities in Solid Fuel Combustion", eds. R. Gupta, T. Wall and L. Baxter. Plenum 1999). In short, this method is based on the behaviour of the ash sample during heating as observed with a microscope using transmitted light.

Ashes sampled from the grate/furnace of the 30 kW test boiler after each combustion test were milled and analysed for residual carbon (loss of ignition).

Combustion test 2

In collaboration with Brigham Young University (BYU), USA, the 12 test samples were test fired at the university which owns a multi-fuel combustor capable of simulating utility-scale combustion conditions. The primary purpose of these tests was to investigate the deposit formation and deposit composition (CCSEM analysis), as well as the corrosion risk of heat surfaces relative to the use of the fuels in utility boilers. A preliminary study has been conducted in a Danish Ph.D. survey using biomass and biomass/coal as fuel.

The tests were carried out at the recently rebuilt multi-fuel flow reactor (MFR) at BYU. The MFR is a down-fired reactor with a reaction length of ~ 2 meters before the sampling position of the deposits. The inner diameter of the reactor is 12 cm.

The facility was heated partly by natural gas, and the simulations of the test represent co-firing of the agricultural residues in a power station fired with natural gas. The natural gas-firing was needed to keep the temperature in the reactor above 850 °C in the zone with the deposition probe. Flame stability was also enhanced and fuel-to-fuel variations in flame temperature were decreased by combining methane with the solid fuels in equal proportions as measured by O_2 consumption. During the tests, the residence time for the biofuels was kept at approx. 1 second, which is similar to power plant conditions, and the oxygen content was 4-5%. The air-cooled sampling probe was maintained at 450-550 °C surface temperature during each test. The duration of all tests was 30 minutes.

Test matrix

The tests conducted at the MFR at BYU both aimed at:

- Evaluation of the fuel mixtures tested at Danish Technological Institute

- Accomplishment of some linearity investigations to see if interactions took place between the inorganics in the fuel.

Therefore, the tests included:

- Investigations of R1 - R12

- Investigations of pure biofuels: Straw, wood, grain screenings, sunflower shells, shea nut shells and sugar beet pulp

- Linearity investigations between mixtures of biofuels.

The results of the tests from which conclusion can be made are: Photos of the deposits formed, deposit mass accumulations, CCSEM analysis of the deposits and chemical analysis of the deposits.

Declaration

In the project application a declaration for biofuel pellets was suggested. The idea was to make a proposal for a declaration in order to meet the consumers need for information about the properties of the biofuel pellets. In the meantime, a European standardisation process for biofuels has been initiated, and due to this, a proposal for a declaration in this specific project makes no sense. In a few years, the standardisation activity will result in a number of standards which will ease the international trade with biofuels and make it possible to define biofuels producing green electricity.

1.2. Conclusions

The conclusion is that the project developed recipes for pellets with satisfactory ash quality and low CO emission from the boiler. In addition, a good pellet quality was developed.

	Total score	Slag in the ash	Fixed slag	Dust fouling	Combustion quality	Pellet quality
Wood pellets	**1**	1	1	1	1	1
R1	**9**	10	-	10	10	6
R2	**8**	10	-	10	6	7
R3	**9**	10	10	10	10	5
R4	**7**	2	10	8	4	10
R5	**6**	2	10	10	2	7
R6	**4**	2	9	3	3	3
R7	**4**	2	9	4	2	2
R8	**4**	2	9	4	2	2
R9	**5**	4	10	4	2	3
R10	**5**	4	10	5	2	2
R11	**4**	2	8	2	2	4
R12	**4**	6	8	2	1	2

*Table 1-2. Evaluation of recipes. Marks: 1 is the best and 10 the poorest. R1-R2 were given no marks in "fixed slag" because the test periods were too short for evaluating this parameter. The evaluation clearly indicates that wood pellets are in a class by themselves, just as it is very clear that R1-R3 are in a class by themselves - but at the other end of the scale. R4 and R5 are evaluated to be poor primarily because of the poor pellet quality and heavy dust fouling in combustion chamber and flue gas tubes. **R6, R7, R8, R11 and R12 are evaluated to be the best pellets even despite of dissimilarities in the parameters.***

Reciept	Fuel pellet	Additive	"Category"
R8	2/3 grain screenings, 1/3 sunflower	limestone, 5 %	
R7	2/3 grain screenings, 1/3 wood	limestone, 5 %	
R9	2/3 grain screenings, 1/3 sheanut	limestone, 5 %	
R6	2/3 straw, 1/3 wood	limestone, 5 %	**I**
R12	2/3 grain screenings, 1/3 sheanut	limestone, 3 %	
R10	1/1 grain screenings	limestone, 5 %	
R5	2/3 straw, 1/3 wood	Al(OH)3, 5 %	
R4	2/3 straw, 1/3 wood	limestone, 5 %	
R11	2/3 grain screenings, 1/3 wood	limestone, 3 %	**II**
R2	1/1 straw	kaolin, 2%	
R3	1/1 straw	CaO, 1%	
R1	1/1 straw	Al(OH)3, 1%	**III**

Table 1-3. Recipes "ranked" according to their melt area fraction in the temperature range 900-1000 °C. The result is very close to Table 1-3 as R6, R7 and R8 are in the best group in both tables. R1, R2 and R3 are in the poorest group.

Total costs	DKK/ton	GJ/tons	DKK/GJ
R1	1,075	15.30	70.25
R2	1,083	15.10	71.71
R3	1,072	15.20	70.51
R4	1,156	15.40	75.05
R5	1,333	15.20	87.68
R6	1,283	16.20	79.19
R7	1,146	15.30	74.90
R8	1,148	15.50	74.04
R9	1,122	14.70	76.34
R10	988	14.30	69.10
R11	1,118	15.60	71.68
R12	1,029	14.80	69.56
Pellets of sawdust	1,368	17.28	79.17
Pellets of dried logs	1,196	17.28	69.20
Market price, district heating	*1,000*	*17.28*	*57.87*
Market price, private consumer	*1,500*	*17.28*	*86.81*

Table 1-4. The production price for the 12 recipes and wood pellets in tons and per energy unit compared to the wood pellet market prices for district heating plants and private consumers. All prices are exclusive of VAT.

Evaluation of the tests in 30 kW boiler and the analysis

- The production price of the 12 recipes is competitive with the production price of wood pellets. In addition, cheaper additives can be used for commercial production.

- It is possible to make useless biofuels useful by adding additives.

- The combustion quality depends very much on the quality of the pellets, the boiler and the boiler settings, but only limited on the fuel mixture.

- Limestone is the best anti-slagging additive everything considered.

- The pellet quality can be increased considerably when molasses and rapeoil is added.

- A general problem is fouling in combustion chamber and flue gas tubes and fixed slag in combustion chamber primarily at the air nozzles.

- Extra work is always required when using alternative biofuels instead of wood pellets.

- Emissions of dust, NO_x and SO_2 are very high compared to those of wood pellets.

- R6, R7, R8, R11 and R12 gave the best test results, next to wood pellets.

- R1, R2 and R3 gave the poorest results.

- The best biofuel for small boilers is still wood pellets.

2.   Aim and Procedure

By Lars Nikolaisen, Danish Technological Institute

It is the aim of the project to document the technical and economic potential of biofuel pellets produced out of a mixture of various biomass waste products (from forestry and farming) added binding agents and anti-slagging additives. Imported biofuels may also be included. A mixture of 100,000 tons of biofuel of good quality, e.g. wood waste, and 200,000 tons of biofuel of inferior quality, e.g. grain screenings, straw or shea nut shells, may result in 300,000 tons of mixed pellets with known characteristics. This procedure makes it possible to exploit a type of biomass that would otherwise be unfit for energy purposes. I.e. 1 ton of wood waste acts as a catalyst in a process that allows application of 2 tons of another type of biomass of inferior quality for energy purposes.

Combustion tests will be carried out in a laboratory boiler, and the heat surface deposition will also be lab-scale tested. The calorific value of pellets generated from various mixtures of biofuel will be tested and their ash melting properties and composition will be analysed. The prices of raw materials, production and distribution costs will be calculated. The project will also propose a declaration of contents for biofuel pellets.

The project will generate new knowledge of the fuel qualities of mixed pellets at the research level. Another outcome is that end-users are ensured mixed pellets with a declaration of contents probably at competitive prices. End-users are e.g. owners of private household boilers, district heating plants and power utilities.

The primary objective of the project is to compile knowledge of the fuel quality of bio mixtures and to demonstrate that it is possible to produce mixed pellets of a good quality at competitive prices as an alternative to wood pellets. Due to the vast range of biomass products with varying combustion characteristics and raw material prices, it is essential to analyse the cost structure of various products including a few imported products. In recent years, the project partners have gained considerable knowledge on biofuels characteristics and this has generated new and (from an international point of view) unique knowledge of the combustion characteristics of biomass. Thanks to the knowledge compiled in previous projects, it is now possible to generate formulas of biofuel pellets containing a variety of biomass substances along with binding agents and anti-slagging additives.

In the next few years, the market for biofuel pellets – indigenous as well as imported – will most likely expand, and from that point of view it is relevant to examine the behaviour of mixed pellets under a variety of combustion conditions ranging from small-scale boilers to utility-scale boilers. Introduction of mixed pellets with binding agents and anti-slagging additives gives a number of advantages:

1. The production of pellets will be less dependent on raw materials from the wood working industry which is often subjected to fluctuations.

2. It will be possible to use low-cost waste products from farming and forestry.

3. Imported fuels can be utilized although the quality will not be uniform.

4. Through consistency in the analytical procedures and tests applied it is possible to determine the quality characteristics of the pellets.

5. A declaration of contents (biomass, binding agents, anti-slagging additives) will provide consumers with information about the pellet quality.

6. Good biofuels can be used to combust poorer biofuels.

Literature study

Literature will be studied in order to determine the extent of the international research within analysis and combustion test of biofuels with additives (binding agents and anti-slagging additives). This will result in a list of relevant fuels, binding agents and anti-slagging additives which are expected to be suitable for firing in small- and large-scale boilers (district heating and utility boilers). The cost structures, production costs and market requirements will be calculated and evaluated.

Test production

12 samples of 700 kg will be mixed and pelletized from a variety of biofuels added binding agents and anti-slagging additives. A fuel mixture could for instance consist of 33% wood, 33% straw and 33% seed screenings. Anti-slagging additives could for instance be kaolin or limestone. Binding agents could be steam or molasses.

Pellet quality and economy

The hardness and formation of fines in the pellets will be determined. The components will be analysed and the calorific value will be determined. The ash melting characteristics will be determined. The production costs of pellet mixtures will be calculated and so will storage and distribution costs.

Combustion test 1

The 12 samples will be test-fired for 3 days in a 30 kW grate-fired boiler. Emissions and output will be measured, ash/slag and melting behaviour will be analysed and the combustion will be evaluated. The test method has been applied in two previous

projects during which pure non-mixed biofuels without binding agents or anti-slagging additives were tested. This ensures comparability with previous tests.

Analyses

Ash/slag from the test will be analysed and CCSEM analysed (Computer Controlled Scanning Electronic Microscope), an analysis of the structural composition of the slag. The analysis will be compared with the results of the combustion tests and the measured emissions. Through systematic processing of the results, attempts will be made to detect correlation that can be used to predict combustion conditions and the best mixing ratios on the basis of examinations of the fuel.

Combustion test 2

In collaboration with Brigham Young University (BYU), USA, the 12 test samples will be test-fired at the university which owns a multi-fuel combustor capable of simulating utility-scale combustion conditions. The primary purpose of these tests will be to investigate the deposit formation and deposit composition (CCSEM analysis), as well as the corrosion risk of heat surfaces relative to the use of the fuels in utility boilers. A preliminary study has been conducted in a Danish Ph.D. survey using biomass and biomass/coal as fuel.

BYU has several test facilities and to determine which facility to use for the final tests, a number of preliminary tests will be conducted. In the preliminary tests sawdust and pulverised straw intended for the mixed pellets and prepared at the Biotechnological Institute will be tested. One of the purposes of the preliminary tests is to check if the biofuels are prepared correctly for satisfactory handling and combustion at the facilities at BYU. As part of the preliminary test campaign, the experimental set-up for the final test programme will be specified and it will be ensured that the facility is capable of stable operation under the conditions defined. Furthermore, the design of the probes for ash deposition will be evaluated and eventually changed.

Declaration

The project will propose a declaration of content documenting the contents of the mixed pellets.

Evaluation

The collaboration with Brigham Young University makes it possible to evaluate some of the combustion characteristics of the biofuels in a utility boiler without accomplishing full-scale tests.

The outcome of the project can be used by manufacturers of biofuel pellets, district heating plants, industry, power plants and private consumers. From a short-term perspective, manufacturers of biofuel pellets as well as producers of combustion equipment will be able to benefit from the knowledge developed in the project. The main outcome will be increased knowledge of the impact of anti-slagging additives and fuel mixtures on the sintering and fouling behaviour in the boiler. From a long-term perspective, power utilities will also be able to benefit from the project since it may be relevant to apply new (also imported) types of biofuels in biofuel-fired utility boilers, if the price is competitive. In addition, it is most likely that the knowledge compiled by this project relative to combustion of fuel mixtures will be of major relevance to power utilities.

3.   Project Partners

by Lars Nikolaisen, Danish Technological Institute

Danish Technological Institute

Centre for Biofuels is a centre of the Energy Division at Danish Technological Institute. The main task is research and development within energy production on co-generation, district heating, central heating and individual heating with boilers and stoves based on biofuels. An important field of activity is quality characterisation of biofuels including energy crops. In 1995, Centre for Biofuels was appointed by the Danish Energy Agency as National Test Laboratory for Small Biofuel Boilers. The main objective of the laboratory is to approve the performance, reliability and efficiency of boilers according to government specifications. Until 2001, type approved boilers received subsidies from the government.

Since 1994, Centre for Biofuels has been involved in tests of biofuel quality. The first project was a study of combustion quality of straw pellets with various additives such as lignosulfonate, kaolinite and various types of chalk. The project indicated that anti-slagging additives could be interesting as subject for a more detailed study. From 1995 to 1997 Centre for Biofuels participated in a full-scale test regarding the use of grain as energy crops in power plants and district heating plants. It was possible to mowe, bale, transport, store and burn the grain/straw, and one of the main conclusions was, that grain alone or together with straw - from a technical point of view - might be an interesting alternative as fuel in larger plants. In 1999, Centre for Biofuels tested six different small-scale boilers' ability to burn energy crops and agricultural residues such as miscanthus, willow, pea shells, rape, triticale and rye. From 1997 to 2001 Centre for Biofuels participated in the national energy crops programme. The Test Laboratory tested the combustion quality of 20 different energy crops. The crops were different sorts of rye, different sorts of triticale and miscanthus, oats, hemp, willow, sunflower and reed canary grass.

dk-TEKNIK ENERGY & ENVIRONMENT

dk-TEKNIK ENERGY & ENVIRONMENT was founded in 1918 by Danish boiler owners as a fuel laboratory. Coal was the dominating fuel at that time. Later, oil became the primary energy source for power production, but due to the oil crisis in the beginning of the seventies, the power stations were converted back to coal. In the late eighties, biomass came into focus as energy source for district heating. A large number of straw-fired facilities (effect approx. 1-10 MW heat) were established during the following years. During this period dk-TEKNIK participated in several projects on slagging and corrosion problems. One of the most successful efforts was a study of the combustion, slagging, and emission behaviour of 12 different carefully selected straw qualities.

From 1995 to 1998, dk-TEKNIK carried out a major research project on the composition and melting behaviour of straw ashes in co-operation with the Danish Technical University and the Geological Survey of Denmark and Greenland. In this project dk-TEKNIK developed a method for determining Melt Area Fractions (MAF) for biomass ashes as an alternative or supplement to the standard coal ash fusibility test (ISO 540 or similar). At present, dk-TEKNIK participates in a European pre-standardisation project called BIONORM on biomass analyses with more than 30 partners. In BIONORM the MAF-method will be tested as a candidate to a future European standard in competition with other methods. Since the foundation in 1918, dk-TEKNIK has been actively involved in standardisation work and will continue to put fingerprints on future standards concerning fuel characterisation and emission monitoring.

Biotechnological Institute

Biotechnological Institute is an independent contract research and consultancy organisation and is a key partner in the knowledge network of innovative companies in the biomedicine, biotechnology, and food industry. The Division of Applied Food Technology works within the areas of development, consultancy and tests in relation to production hygiene, hygienic design, and new innovative processes including processing of biofuels. In addition, the Division owns a pilot plant facility in Sdr. Stenderup near Kolding.

The pilot plant facility has equipment for grinding, pelletizing and extruding of feedstuffs and food. For many years, the Biotechnological Institute has been engaged in process and product development of new products as well as testing and documentation of existing products. Especially within the field of pelletizing techniques, many tests have been carried out in the past years, partly through funded projects and partly as client assignments/contract work. The Division has carried out extensive work on straw with focus on the utilization of straw fibres for chipboards, cellulose and fuel. In 1994, Biotechnological Institute participated in a fuel project together with Danish Technological Institute during which the suitability of straw and wood pellets in small boilers was investigated.

Tech-wise

Tech-wise is a consulting engineering company with approx. 200 employees. Tech-wise is a subsidiary of the Elsam utility group, which operates 5,000 MW_e of power plants of which the majority are combined heat and power (CHP) plants.

Techwise's involvement in the utilisation of biomass for power production has been going on for more than a decade and has its background in political decisions made by the Danish Government aiming at achieving a substantial reduction of the CO_2 emission. As a result, the Danish power utilities are obliged to utilise large quantities of biomass for power production. In order to find the optimum way to fulfil this obligation, a large and still ongoing R&D programme was initiated by Elsam, and Tech-wise has been actively engaged in all the R&D activities.

The R&D activities include investigations of availability and quality of biomass, development of conversion technologies (CFB technology, grate-firing technology, co-firing with coal, gasification, pyrolysis) as well as R&D on specific issues such as logistics, corrosion, slagging, emissions, residual products, etc. Tech-wise has build up comprehensive knowledge of biofuels ranging from growing, harvesting, handling, sorting and treating biomass before utilisation in the power plant. Since many biofuels are waste products from a number of industrial processes, these are also recorded in the files. Several of these projects have been partially funded by the EU and carried out in cooperation with research institutions, utilities and suppliers all over Europe.

Tech-wise has been involved in the engineering of biomass plants in Denmark as well as abroad. The involvement in biomass mainly covers plants using straw and wood chips as fuel and with a power output from 2 to 40 MW_e.

References: Rudkøbing CHP Plant (straw); Måbjerg CHP Plant (straw, wood, municipal waste, natural gas); Grenå CHP Plant (straw, coal, agricultural wastes); Ensted Power Plant (straw, wood); Ostroleka CHP Plant, Poland (wood); Midtkraft Co-firing Power Plant, 150 MW_e (straw); Midtkraft Co-firing Power Plant, 400 MW_e (straw); Thetford Chicken Litter Power Plant (chicken litter); EHN, Spain 25 MW_e (straw, wood); Biomasse Italia 80 MW_e (wood); Alliant Energy, USA 650 MW_e (switchgrass). Additional project experiences with biomass technology are available for Denmark, Spain, England, Italy and Poland. For studies and feasibility studies Tech-wise can also refer to the Czech Republic. From the plants in operation – especially the plants operated by Elsam – Tech-wise has achieved comprehensive knowledge of operation and maintenance of biomass plants.

Brigham Young University

Located in Provo, Utah, Brigham Young University (BYU) has a student body of 30,000 with 1,589 faculty. BYU has 11 colleges offering bachelor's degrees in 212 academic programs, master's degrees in 70 and doctorates in 20. The Department of Chemical Engineering at BYU was formed in 1958.The undergraduate program was first accredited in 1961, with the Masters degree and PhD programs receiving approval in 1962 and 1968, respectively. Today, the department has 14 full-time faculty, about 350 undergraduate students and 45 graduate students.

Within the Department of Chemical Engineering, research involves all levels of undergraduate and graduate students. Research topics vary widely, including such areas as biomedical engineering, catalysis, combustion, electrochemical engineering, energy, environmental engineering, teaching pedagogy, and thermodynamics.

Numerous laboratories are maintained by the Department of Chemical Engineering for combustion research, including the Combustion Computations Laboratory, the Solids Reactions Laboratory, the Catalysis Combustion Kinetics and Surface Analysis Laboratory, the Flame Diagnostics Laboratory and the Combustion and Reactions Laboratory. These laboratories offer the use of several drop tube reactors, multiple

spectrometers, capillary gas chromatographs, supercritical fluid chromatographs, workstations (HP, Sun, Dec and SGI) a flat frame burner (FFB), a controlled profile reactor (CPR), a multi-fuel combustor (MFC), and a laminar flow reactor.

Under the direction of key Chemical Engineering faculty at BYU, the Advanced Combustion Engineering Research Center (ACERC) was founded in 1985 by the National Science Foundation (only 5 Engineering Research Centers were funded out of over 100 applications from major universities). ACERC is a collaboration between BYU and the University of Utah researching topics including combustion chemistry, Nox and other pollutants, fine particles, coal pyrolysis, char oxidation and simulation using computational fluid dynamics (CFD). Research in combustion is also being done by the Combustion Laboratory at BYU within the areas of coal combustion, biomass combustion and co-firing, black liquor processing, selective catalytic reduction (SCR) deactivation, corrosion, ash deposition and boiler modelling. The Department of Chemical Engineering at BYU was also selected by the Design Institute for Physical Property Data (DIPPR), an organisation of the national American Institute of Chemical Engineers (AIChE), in 1998 to manage and upgrade its large database of thermophysical properties.

Sprout-Matador

Sprout-Matador and United Milling Technology (UMT) forms the FEED TECHNOLOGY division of Andritz AG, which is a large industrial group of companies with head quarter in Austria. At 14 sites located in Austria, Germany, Finland, Denmark, France, USA, Canada, Australia and China, the Andritz Group develops and manufactures pulp equipment, paper making equipment, equipment for the steel industry, hydraulic machinery, environmental equipment, and equipment for the feed and energy production industries.

In recent years, the feed technology business sector of Andritz has seen a very favourable development with a world-wide dynamic growth in all areas. The head quarter of the ANDRITZ FEED TECHNOLOGY is situated at Sprout-Matador A/S, Denmark. Together with Sprout-Matador, USA and UMT, Holland, the ANDRITZ FEED TECHNOLOGY today is the worlds largest company for development, manufacture and sales of processing machines and systems for the industrial manufacture of animal feeds, pet foods, aquatic feeds, and fuel pellets. SPROUT-MATADOR and UMT's manufacturing facilities in Denmark, Holland and the USA are known throughout the feed processing industry as producers of superior machines for more than a century. 400 employees are developing cost-efficient, environmentally friendly systems for pellet producers all over the world. Regional sales offices operate in Sweden, United Kingdom, USA, Canada, Chile, Venezuela and China. A special department for biomass technology was established by Sprout-Matador in 1986 in Esbjerg. During the past 16 years SPROUT-MATADOR has supplied equipment for grinding and pelletizing of biofuel products to a large number of private pellet manufacturers and public incinerator plants all over the world, corresponding to an annual capacity of more than 1.5 million tons of fuel pellets which in terms of energy corresponds to 7.2 million MWh.

4.   Literature Study

By Klaus Hjuler, dk-TEKNIK ENERGI & MILJØ

4.1.   Additives for slag abatement

The behaviour of the inorganic (ash) part of solid fuels has long been recognised as being critical to design and operation of boilers. Deposit formation, fouling and corrosion of furnace and superheater surfaces cause significant increase in downtime and decrease of boiler efficiency and metal lifetime.

The interest in sustainable energy production using renewable and carbon dioxide neutral biomass fuels has increased the concern regarding these problems, which are related to the content of potassium, chlorine and silicon, especially in annual crops. In general, biomass ash is low melting, and significant quantities of potassium and chlorine may be evaporated from the fuel during combustion. Condensation of potassium chloride on surfaces initiate ash deposition as well as chlorine-induced high temperature corrosion. Further reactions with particles and gas phase elements take place resulting in matured deposits that may be very dense and hard to remove.

Plenty of literature is available on slagging and fouling problems in coal-fired boilers. Benson (2000) gives a summary on ash formation and behaviour in pulverised coal-fired utility boilers. For a more specific summary about deposition during biomass combustion is referred to Miles (2000) that discusses results from a major research project on formation of alkali deposits (Sandia and NREL, 1996).

4.2.   Prevention of deposit formation

The traditional way of handling deposition problems on larger utilities is the use of soot blowing with steam, water or pressurised air. Ball cleaning devices are frequently used in smaller plants. Operational measures such as reduction of the furnace load, reduction of furnace exit gas temperature and increase of the air to fuel ratio may have some effect. The last mentioned is primarily to obtain more oxidised conditions in the furnace, producing oxides rather than reduced ash species. Design measures such as larger heat transfer areas and exchangeable superheaters are also possible.

An alternative way is modification of the solid fuel (ash) or furnace chemistry using additives (inorganic materials). A major supplier is the company ERC Emission Reduction Concepts GmbH that has specialised in the use of additives and is a major producer of process additives for burning fossil and biomass energy sources. ERC manufactures, distributes and engineers additives for combustion improvement, emission reduction (e.g. CO, C_xH_y, SO_3, NO_x, dioxins) and on corrosion prevention. Equipment such as dosing systems is also part of the ERC production range. ERC has a product range called "Carbamin" additives claimed to be suited for the combustion of solid fuels like coal, wood, refuse or sewage. This range includes:

- Combustion catalysts for stabilising the firing, for a quiet, economical boiler operation

- Coating inhibitors, tailored to the various substances used, against the formation of sulphur related coatings and corrosion (fossil fuels)

- Corrosion inhibitors, against chlorine and aerosol related fouling and corrosion with biogenetic fuels (wood, refuse)

However, although additives are marketed and full-scale tests with additives have been conducted for several years in order to reduce slagging and deposition in coal-fired boilers, the use of additives has not yet found general acceptance. The main reasons may be:

- Costs of dosing systems etc., maintenance and consumables

- Uncertainty about the achievable effects (try it and see)

- Adverse effects on the residue for cement production etc.

4.3. Use of additives in grate and suspension fired boilers

Numerous references can be found in literature that report on additive testing in coal boilers. Unfortunately, it is impossible to extract generally applicable knowledge about which additive should be selected under which circumstances (fuel type, boiler type, means of injection etc.). The use of various additives and/or addition methods is covered by a number of patents of which the most recent found in this work (US patent 5.894.806, 1999) describes a method of targeting injection of additive by use of CFD-models. It is claimed that this method is efficient and economical because the additive is directed at specific areas where problems are encountered. Additives are typically slurries of $Mg(OH)_2$ or MgO (not covered by the patent). The company FuelTech, Inc. utilizes the technology. An older patent (US 4.577.566, 1986) describes the use of MgO and SiO_2 as powder (0.01-0,25 mm diameter) that are mixed with the fuel or injected to furnace and/or boiler. An alumina silicate material marketed by Atlantic Combustion Products may have similar effects and has been demonstrated for use on bark-fired boilers.

Experiences with additives in smaller biomass boilers are very limited. It is reported that the Præstø straw-fired district heating plant (Sæbye, 1989) had serious problems with depositions on boiler tubes. Addition of Ca-Mg-P based minerals in a very limited quantity of 0.4 kg/ton did not solve the problem, but the deposits were "softened" and cleaning of the tubes was apparently easier. There are no reports on how the additive was injected. At the Borup straw-fired district heating plant (whole bale burner) about 20 kg of limestone per ton straw was added on top of the bales (Sæbye, 1989). The slag produced showed to be somewhat "looser", but not significantly different from the "normal" slag.

Typically, wood pellets are produced with addition of water or steam. However, some producers add lignosulfonates (e.g. Wafolin and LignoBond from Borregaard Lignotech) or potato starch as binding agents (Cronholm et al., 1999). As expected, practical experiences show that pellets with sodium lignosulfonates (such as Lignobond) result in problems with slag formation and deposits in general.

It may be noticed that co-combustion of solid fuels from a mineral matter perspective is comparable to the use of additives due to reactions of the mineral parts of the fuels. This has been demonstrated during full-scale co-combustion test on the Studstrup coal-fired plant, Denmark, with a straw share of 10-20% (energy basis), as well as in the laboratory (Dayton et al., 1999).

4.4. Use of additives in fluid-beds

Additives are regularly applied in fluid-bed combustion and gasification as part of the bed material. In this technology there is intimate contact between the fuel mineral matter and the bed material and defluidization due to sintering/agglomeration is crucial to the operation.

Linjewile and Manzoori (1999) have tested the role of additives during FBC of high-Na and high-K low-rank coals, which like biomass may produce low melting ashes. The additives investigated included dolomite, two types of clay (kaolinite- and sillimanite-rich, kaolinite- and quartz-rich), gibbsite (hydrated alumina). Gibbsite was found to be the most effective material. This was attributed to physical dilution combined with soaking of the melt in the pores of the heated material in contrary to e.g. dolomite that simply diluted the melt.

There are several other reports that materials containing aluminium have effect in prevention of bed agglomeration. Zhang et al. (1999) observed prolonged times (7-10 times) before defluidization in a laboratory spouted bed reactor using bauxite (60.7% Al_2O_3, 26.4% Fe_2O_3) and sillimanite (53.3% Al_2O_3, 43.7% SiO_2) as bed materials. The reactor was fuelled with low rank coals. Öhman and Nordin (2000) have studied the role of kaolin in a lab-scale FB with quartz sand as bed material and straw or bark as fuel. By adding 10% w/w relative to the bed weight, the initial bed agglomeration temperature increased approx. 150 and 10 °C respectively. The effect was attributed to a decreased fraction of the melt being present on the surface on the bed particles, i.e. that coatings were depleted in their content of potassium. Steenari and Lindquist (1998) found that reactions between meta-kaolinite (reaction product of kaolinite, $Al_2O_3 \cdot 2SiO_2$) and potassium from straw formed kalsilite ($KAlSiO_4$) and leucite ($KAlSi_2O_6$), whereas dolomite reacted with silicon to form silicates. No reaction between dolomite and potassium could be detected. CFB combustion of biomass with additives was also studied by Zintl og Ôhman (1998). They experimented with olivine sand, quartz sand, "silver" sand, precalcined dolomite, mullite sand, zirconium sand (ZrSiO4) and sintered magnesite (MgO). Dolomite, mullite and magnesite were shown to be the most efficient in increasing the defluidization temperature. Finally, Kallner and Ljundahl (1998) made tests with combustion of forest residue in a lab-scale FB and found kaolin to effective in reducing the deposition on a simulated super-heater. See Table 4-1.

Name	Class	Subclass	Formula
bauxite	rock	contains gibbsite a. o.	-
colemanite	carbonates	Borates	CaB3O4(OH)3-H2O
dolomite	carbonates	Dolomite	CaMg(CO3)2
magnesite	carbonates	Calcite	MgCO3
calcite	carbonates	Calcite	CaCO3
gibbsite	oxides and hydroxides	-	Al(OH)3
kaolinite	silicates	Clay	Al2Si2O5(OH)4
olivine	silicates	Nesosilicates	(Mg, Fe)2SiO4
mullite	silicates	Nesosilicates	Al6Si2O13
sillimanite	silicates	Nesosilicates	Al2SiO5
zircon	silicates	Nesosilicates	ZrSiO4

Table 4-1. Name and formula of various minerals mentioned above.

4.5. Slagging and fouling indices

A number of so-called slagging and fouling indices have been used by power plant operators for evaluation of the slagging and fouling propensity of coal and coal mixtures during suspension firing. These indices are based on chemical analysis of main inorganic elements in the coal and are briefly discussed in the following.

A "fundamental" coal index is the basic/acid ratio of oxides on weight basis (dry):

$$\mathbf{R_{b/a}} = (Fe_2O_3 + CaO + MgO + Na_2O + K_2O)/(SiO_2 + Al_2O_3 + TiO_2)$$

Fe_2O_3 is here considered as basic and Al_2O_3 as acid. Alternatively the fraction of basic components can be calculated, $R_{b/(a+b)}$. Bryers (1986) made a classical study where eight coal types were fractionated into different particle size classes. The initial deformation temperature (IDT) and the chemical composition of the ashes were determined for each class. A parabolic relationship was found by plotting the IDT versus $R_{b/(a+b)}$ with minimum at an $R_{b/(a+b)}$ of about 0.5.

For evaluation of the slagging propensity, the basic/acid ratio is multiplied with the content of sulphur in the ash (% w/w, dry):

$$\mathbf{R_S} = R_{b/a} \text{ x } S,$$

Values of the slagging-index below 0,6 should not result in slag formation, while values above 2.6 should give serious problems. In the same way, a fouling index is calculated as:

$$\mathbf{R_F} = R_{b/a} \text{ x } (Na_2O + K_2O),$$

where values below 0.6 are acceptable, while values above 40 indicate seriously fouling coals (Zelkowski, 1986). The fouling-index expresses the propensity of the ash to adhere on surfaces (being partially melted).

In addition, a silicon ratio is being used to indicate the viscosity of the slag melt, defined as:

$$\textbf{SR} = SiO_2/(SiO_2 + Fe_2O_3 + CaO + MgO)$$

High SR values (> 0.72) indicate high viscosity, i.e. low slagging propensity, whereas low SR values (< 0.65) indicate low viscosity.

The propensity of biomass for deposit formation has primarily been related to the content of sodium and especially potassium. The ratio of alkali metal to silicon was proposed as a deposit-index for biomass (FEC Consultants, 1988):

$$\textbf{AR} = (Na_2O + K_2O)/SiO_2$$

Fouling is reported to be "certain" at a ratio of about 2 and above, while the range from about $0.3 - 2$ is associated with risk of fouling. The absolute content of alkali in the fuel can be indicative as well. A major research effort on biomass alkali deposits concluded that the deposit propensity increases in the range 0.17-0.34 kg alkali/GJ, dry basis. Above 0.34 kg/GJ deposits are certainly formed and slag formation is possible.

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5.   Development of Recipes for the 12 Mixtures

By Lars Nikolaisen, Danish Technological Institute

5.1.   Market survey for biofuels

The well-known market for raw materials for bioenergy in Denmark is limited to straw, wood chips, firewood and dry and wet wood residues from industries. However, other residues are available which are normally not used for energy. Due to large annual amounts, some of them cause problems for the fodder producing industry, others are limited in amount and produced in various geographic regions. For the fodder industry the protein content of the residue is an important factor. If the market price for protein is low, higher quality products (soy, etc.) are used for fodder, and the amount of biowaste increases. When the protein price increases, some of the biowaste is used as it still has a certain content of protein. This mechanism means that a predicted biowaste supply to the energy sector will be unstable and determined by among others the world market prices for food and fodder ingredients.

The study of the Danish market showed that large amounts of grain screenings are available, but the amount varies from year to year. Seed screenings are available in smaller amounts. Beans and peas are polished and the dust is normally used for fodder, but some years there is a small surplus of pea waste on the market. The residues from Danish plant oil production from rape and overseas seeds and nuts (soy, shea, sunflower and cacao) are sometimes available on the energy market, at least shea nuts are sold as pellets and so are sunflower residues. The plant oil producing industry is very competitive, and it is not possible to get information about annual production rates for residues, etc. In Denmark residues from coffee bean production are limited to a few hundred tons a year. There is a very large production of residues from sugar beets. After extraction of sugar from the beets, the pulp is dried, molasses is added and thus made into valuable fodder for animals. Sometimes there is a surplus and some thousand tons are sold on the energy market. However, the price is still too high for energy purposes as the high fibre content in the beet residue makes it an attractive and expensive product. This is a pity as preliminary tests have shown no slagging tendencies and a good combustion quality. The reason is probably that the alkali components are washed out during the sugar production process. Finally, olive stones are available in Denmark from 2002.

The conclusion of this market survey in Denmark is that grain screenings and straw are recommended as main ingredients in the recipes and - in smaller amounts - sawdust (dry wood waste), shea residues and sunflower residues. Three batches of straw were tested for K in order to find the most problematic straw. The batch with the highest K content was used, as K will lower the ash melting temperature. The K content was 1,39% dm.

The survey regarding additives was carried out in order to check if the additives from the literature study were on sale. The additives are limestone, aluminium hydroxide, kaolinite and calcium oxide (CaO).

The literature study showed that Al might be interesting, possibly together with Si, as Si changes the reaction of the additive. Various types of chalk were another option. Due to the fact that especially small boilers have problems with high ash content, it was decided that the recipes should not have an ash content higher than approx. 10%. The main purpose of the additive is to increase the melting temperature of the ash. Another important purpose is to trap K in the bottom ash and thereby prevent a lot of fly ash in the flue gas system.

5.2.   Discussion of recipes

For small boilers the most important requirement as to fuel quality is that the ash is smooth and fine like powder without any slagging formations. For utility boilers the demand is more complex, among other things the chemical composition of the ash formations on the heat surface is important due to high temperature corrosion.

The development of recipes during the project was an iterative process during which a few recipes were produced and tested and conclusions were made before the next recipes were decided.

It was decided to minimise the amount of additives and to try three different additives in recipes R1, R2 and R3. From previous experiments it was known that kaolinite is very efficient when mixed with straw. The two Al additives was $Al(OH)_3$ and kaolinite and the third additive was calcium based CaO. Straw was the raw material. In order to get the same Al content in R2 and R1, it was necessary to add 2% kaolinite to R2.

The first 3 recipes were:

R1: Straw + 1% w/w Al(OH)$_3$
R2: Straw + 2% w/w kaolinite
R3: Straw + 1%w/w CaO + 3% molasses

The combustion tests in the 30 kW boiler with all 3 recipes were very unsuccessful. A test of 72 hours was initiated, but after 20 hours the boiler was stopped because the combustion chamber was filled with slag, ash, unburned charcoal and pellets. The fly ash emission was very high. R3 ran a few hours more due to increased speed of the grate compared to R1 and R2. There was too much hard slag and the ash screw could not empty the ash box as the slag formed a bridge above the screw.

It was recognised that the amount of additives was too low. It was also necessary to check the effect of adding sawdust in order to keep the ash content low and (probably) increase the combustion quality. To add sawdust to straw is only a dilution of the straw component as there is no catalytic reaction.

The next two recipes were::

R4: 1/3 sawdust + 2/3 straw + 5% limestone (CaCO$_3$)
R5: 1/3 sawdust + 2/3 straw + 5% Al(OH)$_3$ + 5% molasses

The production of R4 resulted in a poor pellet quality, and it was decided to add molasses to R5 as binding agent. The result was a little better than R4, but the pellet quality was still poor. However, the combustion tests in the 30 kW boiler were a success compared to R1, R2 and R3. The combustion gave a smooth and fine ash and there was only a slight slagging tendency at the secondary air nozzles in the combustion chamber. The ash from R5 was the finest of the two and had also a minor slagging tendency at he air nozzles compared to R4. Both tests resulted in much fly ash formation on the heat surface (fouling). This increases the flue gas temperature out of the boiler and decreases the boiler efficiency.

As the R4 and R5 tests were very equal regarding combustion quality, and as limestone is the cheapest additive compared to $AL(OH)_3$, it was decided to make the next recipes with limestone. In order to minimise the additive and optimise the pellet quality it was decided to make R4A, R4B and R4C.

%	R4	R4A	R4B	R4C
Limestone	5	3	3	5
Rapeoil	0	3	6	5
Molasses	0	3	6	5

Table 5-1. Optimising the production and the combustion quality of R4.
The raw material is 1/3 sawdust + 2/3 straw.

Batches of 100 kilos of R4A-R4C were produced and tested in two 15-25 kW villa stokers solely in order to test the slagging tendency. R4A and R4B resulted in a fine ash with minor pearls of green slag. R4C did not produce green pearls, but some very fragile slagg skeletons which could be crushed between two fingers. On the basis of this preliminary test, it was decided that R6 should be identical with recipe R4C, and R7 should be like R6, except that straw should be substituted with grain screenings.

R6: 1/3 sawdust + 2/3 straw + 5% $CaCO_3$ + 5% molasses + 5% rapeoil
R7: 1/3 sawdust + 2/3 grain screenings + 5% $CaCO_3$ + 5% molasses + 3% rapeoil

Both R6 and R7 resulted in a good pellet quality. The rapeoil as lubricant in the die was optimised to 3% in R7. The combustion test of R6 gave a fine and smooth ash, but the CO emission was unstable with high peaks. So far, the combustion test with R7 was the best with fine ash and low CO emission.

It was decided that the recipes for R8 and R9 should be like R6, except that sawdust was substituted with sunflower shells and shea nut shells. Ash from grain screenings as well as from shea nut shells contains 3-4 times more Al than ash from straw. Furthermore, the ash content from grain screenings is twice as high as the ash content from straw, whereas shea nut shells are comparable to straw regarding the ash content. The ash of a mixture of grain screenings and shea nut shells will have a relatively high Al content. R10 was a test in order to check non-mixed grain screenings.

R8: 1/3 sunflower shells + 2/3 grain screenings + 5% CaCO$_3$ + 5% molasses + 2% rapeoil

R9: 1/3 shea nut shells + 2/3 grain screenings + 5% CaCO$_3$ + 5% molasses + 2% rapeoil

R10: 1/1 grain screenings + 5% CaCO$_3$ + 5% molasses + 2% rapeoil

In general, the pellets with grain screenings resulted in a good pellet quality. The combustion tests with R8, R9 and R10 in the 30 kW boiler were a success as almost no slagging occurred. All the tests showed a slagging tendency at both the secondary air nozzles and the primary air nozzles in the grate. During all the tests, the air nozzles in the grate were more than half covered with slag when the tests were finished. All the tests showed middle high and many low CO peaks, but in general the CO emission was low.

It was decided that the two last recipes, R11 and R12, should be the two best of R1 - R10, but with reduced additives, binding agents and lubricants. R11 was a repetition of R7 and R12 was a repetition of R9:

R11: 1/3 sawdust + 2/3 grain screenings + 3% CaCO$_3$ + 2% molasses + 2% rapeoil

R12: 1/3 shea nut shells + 2/3 grain screenings + 3% CaCO$_3$ + 0% molasses + 0% rapeoil

The combustion test in the 30 kW boiler showed that R11 produced no slag, but the slag at the air nozzles disturbed the air distribution. R12 resulted in a little more slag in the ash and the air nozzles were covered with slag.

The preliminary conclusion of the project is that pellet recipes were developed with satisfactory ash quality and low CO emission from the boiler. In addition, a fine pellet quality was developed.

6.   Production of 12 Pellet Mixtures

By Jørgen Busk, Biotechnological Institute

6.1.   Raw materials and equipment

The production of 12 pellet mixtures was carried out at the Biotechnological Institute's pilot plant in Sdr. Stenderup. The production of the mixtures was based on the recipes that were developed through the project (see Chapter 5). It was necessary to use 1,500 kg of mixtures for each recipe since 700 kg was required for combustion tests at Danish Technological Institute and approx. 100 kg for other purposes such as tests at Brigham Young University (BYU). The remaining quantity of 600-700 kg was essential for determining the best possible operational conditions through the pellet production.

Raw materials

Raw materials purchased for the tests were:

- Sawdust, primarily as shavings
- Shea nut shells as pellets
- Sunflower shells as pellets
- Grain screenings as pellets
- Wheat straw as pellets

The wheat straw was selected out of three different straw qualities with a high potassium content cultivated on clayey soil. The straw contained approx. 14-15% moisture and was delivered in big bales of 500-600 kg. The straw was cut with a fine cutter, dried and pelletized into pellets of ø8 mm at KFK Alfax. With the exception of sawdust, all raw materials were in the form of pellets and had therefore received the same pre-treatment.

Additives

The following were used in varying quantities as deslagging additives:

- Aluminium hydroxide, $AL(OH)_3$
- Kaolinite, $AL_2O_32SiO_22H_2O$
- Calcium oxide, CaO
- Limestone, $CaCO_3$

Binding agents

The following were added as lubricants and binding agents:

- Rapeseed oil
- Beet molasses
- Water

The rapeseed oil was not heated, but added to the meal at approx. 20 °C. During all the tests the beet molasses was heated to 40 °C.

Pelletizing unit

The production of biofuel pellets was carried out in a feed plant as depicted in Figure 6-1.

Hammer mill

The mill, type Champion, is driven by a 37 kW motor and can be run at two speeds, 2950 and 1450 rpm. The peripheral speed of the hammers are 110 m/sec. at high speed and approx. 55 m/sec. at low speed. The mill is equipped with a 340º screen with an area of 0.43 m^2.

Horizontal mixer

The ground product is led pneumatically from the hammer mill to the mixer which has an effective volume of 2500 litre. The diameter of the rotary mixing blade is 1000 mm and the speed is 27 rpm/min.

Cascade mixer (M6K)

Cascade mixer (7.5 kW motor), type Sprout-Matador, diameter is 400 mm, distance between inlet and outlet is 1600 mm. The cascade mixer operates at 200 rpm/min. and is mounted with 36 mixing paddles. A manifold is mounted on the side with a water discharger and 5 valves through which steam is added to the meal. The outlet temperature of the meal is measured with a pt100 sensor.

Steam

Steam is generated in a high pressure boiler, type Dan Stoker, maximum yield 400 kg/h. The boiler operates at a pressure of 4-5 bars and the steam is reduced to 2 bars before entering the cascade mixer.

Pellet press, M5 and M12

R1 and R2 are pelletized by a M5 press (37 kW motor), type Sprout-Matador, with a vertical rotating ring die and two rollers. The dimensions of the die are: internal diameter 355 mm and effective width 95 mm. R3-R12 are pelletized by a M12 press (90 kW motor), type Sprout-Matador, with a vertical rotating die and 3 rollers. The dimensions of the die are: internal diameter 508 mm and effective width 156 mm.

Belt cooler

BEMA belt cooler, single deck, length 550 cm and width 150 cm. The cooler is equipped with a variable speed regulator with a maximum retention time of 20 minutes. For cold air supply the cooler has two ventilators with a maximum capacity of 13000 m^3/h.

Bagging

After the cooler the pellets are conveyed by a bucket elevator to a vibrating sieve which screens the fines and the pellets are bagged in bigbags.
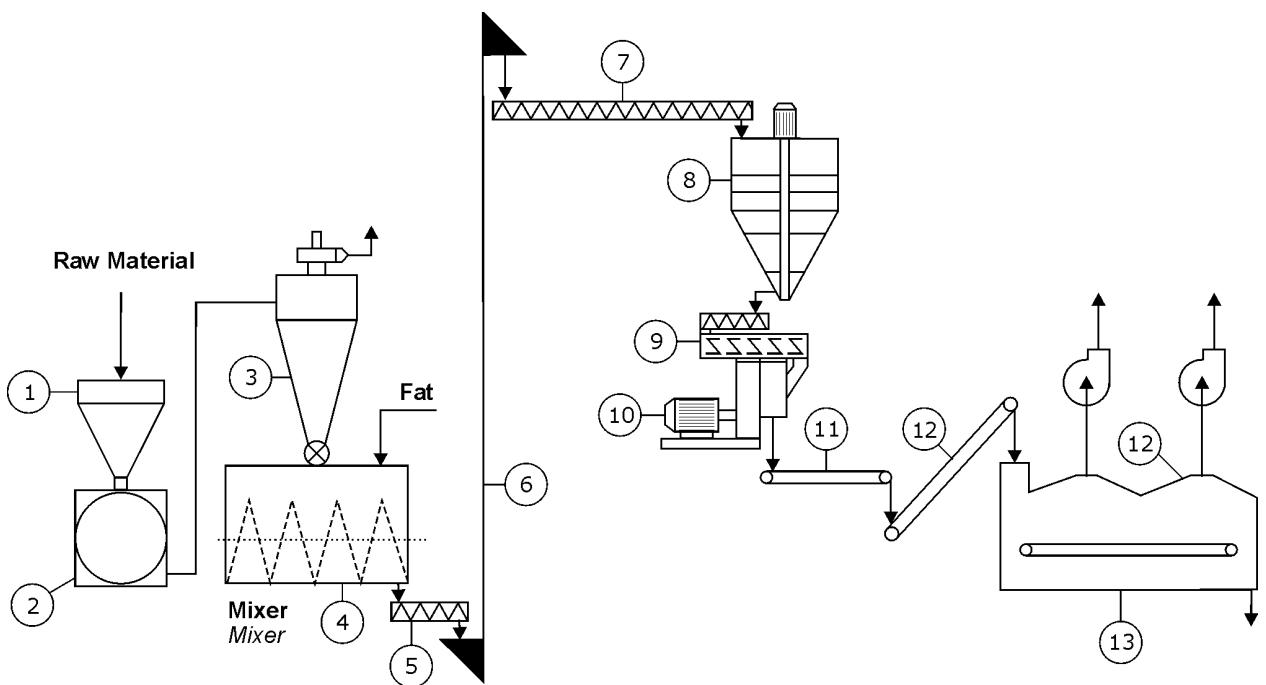
1. Pre-Bin
2. Hammer Mill
3. Cyclone
4. Horizontal Mixer
5. Screw
6. Bucket Elevator
7. Screw

8. Pre-Bin
9. Caskade mixer
10. Pellet Press
11. Belt Conveyor
12. Belt Conveyor
13. Cooler

Figure 6-1. Feed Milling Plant at the pilot plant in Sønder Stenderup

6.2.   Method of producing biofuel pellets

All the raw materials were weighed individually before grinding and mixing. The raw materials were ground in the hammer mill on a ø4.0 mm screen. The mill operated at 1450 rpm at a peripheral speed of 55 m/sec. By using this screen and at this mill speed, the individual raw materials will be evenly and adequately ground to produce a good structure and without significant quantities of fine dust.

Mixing and dosing

From the hammer mill the meal is carried pneumatically to the horizontal mixer in which the ground products are mixed with additives and binding agents for a minimum of 10 minutes. In all the tests the meal was conditioned for a minimum of 1 hour before pelletizing.

By means of a dosing screw with variable speed from the mixer, dosing and capacity during pelletizing can be regulated. From the mixer to the cascade mixer the meal is transported by a bucket elevator and a screw conveyor.

Addition of steam

If necessary, steam and water are added to the meal in the cascade mixer (M6K). The steam is led into a manifold and dosed through valves into the meal. At the outlet of the cascade mixer the meal temperature is measured with a pt100 sensor.

Water is added in the first part of the cascade mixer and mixed effectively into the meal. The retention time of the meal in the cascade mixer is 25-30 seconds.

Pelletizing

As mentioned earlier, two presses were used. On the M5 press a die of ø12 x 80 mm was used. This press was only used in production R1 and R2 because the motor (37 kW) was inadequate for the types of mixtures chosen.

When producing R3, R4 and R5, the mixtures were pelletized on an M12 press (90 kW) with a die of ø12 x 110 mm die. During production of R6-R12 the same die was changed to ø12 x 108 P96 mm (P is the length of the press channel).

Cooling

The pellets were cooled on a belt cooler for 20 minutes. During all the productions the pellets were cooled down to approx. 5 ℃ above the air temperature. After cooling, the pellets were sifted on a 10 x 10 mm vibrating screen and bagged in big bags. During bagging samples were taken for analysis. In order to measure fines in the product, samples were taken of the hot pellets which were cooled in special cooling boxes.

Choice of die

For optimal combustion tests, comparable with earlier tests, the pellets should have a minimum diameter of 8 mm, preferably up to diameter 12 mm. Initially, in R1, a test was carried out with a ø9 x 85 P40 mm die on straw. But this die was unsuitable. Normal and sound straw pellets could not be pelletized.

Based on the industrial production of wood pellets and straw pellets it is typical to use dies with a ratio between pellet diameter (D) and die thickness or the length of the hole in the die (L) of 1:7.5 for wood, and 1:10-11 for straw. It was decided to try with a die of ø12 x 80 mm (1:6.7).

The tests with straw have shown that good pellet quality can be produced, but the motor on the M5 press was loaded to its maximum at low capacity. For higher capacity and thus more uniform pellets only 2 tests were carried out with this press.

For the M12 press, which is considerably larger (90 kW motor) with 3 press rollers, a die of ø12 x 110 mm with a D:L ratio 1:9 was chosen. When pelletizing a mixture of straw, burnt lime and molasses (R3) the press operated steadily with good pellet quality. But power consumption was high and there was a tendency to overheating of the die, which indicates that the ratio between the pellet diameter and the die thickness of the die is excessive.

R4 and R5, a mixture of straw and sawdust to which 5% aluminium hydroxide and 5% limestone had been added, was very difficult to pelletize with a die of ø12 x 110 mm. A mixture of straw and sawdust to which 5% additives were added were both with and without addition of water, a mixture with poor lubricating and binding attributes which caused much resistance in the die. This pronounced resistance caused the extreme overheating of the die and the press rollers grinding the meal before it was pressed through the holes. Evaporation from the hot pellets/fines was very high. This type of mixture requires the addition of substances that both lubricate and act as binding agents, and another type of die with a lower ratio between the diameter of the hole and the thickness of the die.

Therefore, the die of ø12 x 110 mm was altered. Practical experience has proved that it helps to surface-grind the die on the inside so that counter-sinking is almost non-existent. This reduces the die's efficiency in compressing the meal into the holes. Furthermore, the die was relieved with a 13 mm drill approx. 12 mm into the die. The effective press channel was thus reduced from 110 mm to 96 mm. The new dimensions were ø12 x 108 P96 mm. Relieving of a die causes the reduction of pressure because the hole in the outer part of the die gets bigger.

Sampling

Samples of all raw materials and samples of meal mixtures at the outlet of the horizontal mixer were taken in order to determine the moisture content. After the pellet press, samples were taken to determine fines in the product. After the cooler, samples were taken for determining moisture, formation of fines and pellet hardness including bulk density.

Recording and analysis

During pelletizing, data was collected both manually and on a computer.

Energy consumption of the pellet press is recorded by reading the ampere consumption when samples are extracted for measuring capacity. Based on the recorded power consumption in amperes, the consumption in kWh/tons can be calculated:

$$\text{Effect } P = \frac{\sqrt{3} \cdot V \cdot amp \cdot \cos\varphi}{1000} \text{ in kW} \qquad \text{Consumption} = P/\text{capacity in kWh/tons}$$

V	=	380 volt
amp	=	recorded ampere
cos φ	=	0.87
capacity	=	recorded capacity in tons/hour

When calculating kWh/tons only the net consumption for pelletizing is included. Idle speed consumption was deducted in order to make it easier to compare different pellet qualities. In the case of the M12 press this amounts to 55 amp and for the M5 press 25 amp.

Meal temperature, °C, was partly measured on cold meal at the beginning of a test and partly after the addition of steam in the cascade mixer. The difference is used in calculating steam in %. We have calculated on a rise in temperature of 14 °C = 1% steam.

Pellet temperature, °C, in the hot pellets was been measured on the samples taken directly after the pellet press. The sample is kept in a thermo bottle and measured with a calibrated digital thermometer, Testo 925.

Fines in product, %, are from sample taken after the press and cooled. The analysis was determined by taking a homogeneous sample of 500 g and sifting it on a ø10 mm sieve (pellets are ø12 mm). The quantity of fines after sifting corresponds to the return flow which leads from the sieve after the cooler to the meal pre-bin of the pellet press.

Formation of fines, %, is determined according to the ASAE Standard 269-1 (Agricultural Engineers Year Book, 1966). Fine formation was measured by sifting a representative sample on a mesh whose holes are slightly smaller than the diameter of the pellets. In the case of ø12 mm pellets, a ø10 mm mesh is used. 500 g sifted pellets were put in a box with the measures 300 x 300 x 130 mm. The box was rotated at 50 rpm/min. for 10 minutes. Then, the fines were sifted from the pellets and the pellets were weighed. Fines were calculated in percentage of the fines-free total sample.

KAHL hardness test, kg, is an expression of the extent to which a pellet can be exposed without cracking or bursting into pieces. The pellet is placed between 2 "jaws" with a spring screw-clip. The pressure in kg is given on a scale from 0-100 kg.

Moisture, %, in raw materials and fuel pellets are measured in a heating chamber at 105 °C for minimum 4 hours.

Bulk density, kg/m^3, is measured in a 25 L pail. The content in kg is multiplied by 40 in order to obtain the specific weight in kg per m^3.

6.3. Progress of the 12 productions

The tests consisted of 12 mixtures of various biofuels to which additives and binding agents were added. For each recipe a mixture of 1,500 kg was calculated. 700 kg pellets for combustion tests, 700 kg for optimising the pelletizing process and approx. 100 kg for other purposes. Possibilities for determining optimal operational conditions for each recipe was limited and it is therefore possible that a few of the mixtures could have been produced in a more optimal manner. The composition and quantity of additive has great influence on the pelletizing attributes of each mixture.

As regards the choice of die, the specified pellet size was min. ø8 mm and up to ø12 mm.

In all the tests steam was added in the cascade mixer. Effective heating of the meal is necessary in order to activate the raw materials and binding agents. A suitable quantity of water works as a binding agent. The composition and technical data are shown in Table 6-1 and 6-2.

Recipe R1

This mixture consists of 98.9% wheat straw and 1.1% $AL(OH)_3$.

The intention was to pelletize the mixture on an M12 press with a ø9.0 x 85 P40 mm. But the pre-test with various quantities of water and steam and capacities showed that the length of the press channel was too short. The pellets were neither firm nor cohesive and there were holes in the die where the meal flowed through. This necessitated the change to an M5 press with a die of ø12 x 80 mm.

With this press and die it was possible to run 400 kg/h and to produce pellets of a reasonably good quality. The low quantity of additive has no influence on the mixture's pelletizing attributes.

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Recipe R2

This mixture consists of 98.0% wheat straw and 2.0% kaolinite.

The mixture was pelletized on the M5 press, ø12 x 80 mm die. A small sample proved that it was necessary to add more water to the meal in the mixer (5.5%), and in the cascade mixer, too. This might be due to the fact that kaolinite absorbs moisture. Without more water in the cascade mixer the pellets were short and irregular. The press operated better with water and the quality of the pellets was reasonably good.

Recipe R3

This mixture consists of 95.5% wheat straw, 1.3% burnt lime (CaO) and 3.2% beet molasses.

In order to obtain the desired effect of burnt lime, a liquid mixture was produced containing 1 part of CaO, 3 parts of molasses and 6 parts of water. When CaO and water are mixed together, heat is developed and slaked lime is formed which settles at the bottom of the vessel. Long and vigorous stirring was necessary to dissolve the lime in water and molasses. For this an Ultra Turrax which is a very fast knife stirrer was used. This cuts the particles into pieces and accelerates the reaction between lime and water. The liquid reaches approx. 90-100 °C. When the reaction is completed the liquid is homogeneous and settles slightly after standing for 16 hours. The preparation of the liquid requires special equipment and safety precautions.

After grinding the straw, the liquid was added to the mixer. The M12 press with a die of ø12 x 110 mm was used for pelletizing. The pelletizing process went reasonably well, but the addition of up to 7% water in the cascade mixer was necessary in order to achieve stable operation of the press and a satisfactory pellet quality. Without extra water in the cascade mixer the pellets were short and crumbly. It is important that maximum amounts of steam are added. Too little steam increases the power consumption of the press. The rate of evaporation was high during pelletizing which indicates an incorrect ratio between the mixture's pelletizing attributes and the dimensions of the die.

R1-R3 were based on wheat straw to which additives and binding agents were added. When optimising the process, focus of attention must be on the choice of die. With the correct die and quantity of water, capacity can be increased. An increased flow through the die produces a better and more uniform pellet quality and will reduce electricity consumption significantly.

Recipe R4

This mixture consists of 63.8% wheat straw, 31.4% sawdust and 4.8% limestone, $CaCO_3$.

The pelletizing of this mixture caused many problems. The tests showed that it was impossible to produce pellets without adding a considerable amount of water followed by a conditioning time of more than 2 hours. The meal mixture contained 10% of water and could - together with a maximum quantity of steam - not be pelletized (90% fines). Due to the limited amount of raw materials water was added, so the total amount of water before pressing was approx. 20%. In general, the pellet quality was poor, and after cooling and sifting 40% fines was found in the product which was returned to be re-pelleted. The die was overheated, hence the high rate of evaporation and the short pellets with poor cohesion. This can be seen in the analyses of fines and hardness which were measured to be 34.2% and 8.5 kg, respectively.

This test showed that the mixture of sawdust and straw together with 5% limestone are more difficult to pelletize than pure straw mixtures. The capacity was low and the power consumption relatively high.

Recipe R5

This mixture consists of 60.7% wheat straw, 30.0% sawdust, 4.8% $Al(OH)_3$ and 4.5% beet molasses.

R5 is the same recipe as R4 except that limestone has been replaced with aluminium hydroxide.

Since the recipe R4 was difficult to pelletize, it was agreed that 5% molasses could be used as a lubricant and binding agent. The quantity of water added to the meal in the mixer was reduced to 7% and during pelletizing varying quantities of up to 7% water was added in the cascade mixer.

Due to the high resistance in the die, this mixture was also pelletized with a capacity of only 400 kg/h. This is the reason for the large quantity of fines in the product which was returned for re-pelletizing. At low capacity the holes in the hot die were not filled sufficiently and the rate of flow was low. The meal passed the die partly as fines and partly as short and long pellets. The molasses acted as a binding agent, but lubrication was poor and this increased counter-pressure in the die.

The high rate of evaporation during pelletizing is the reason why there is only 6.0% moisture left in the cooled pellets.

R4 and R5, based on straw and sawdust, showed that it would be untenable to continue pelletizing without lubricants and binding agents as well as a change of die. Sawdust and straw together with 5% limestone or aluminium hydroxide is difficult to pelletize. It was decided that the die should be renovated and the amounts of lubricants and binding agents should be discussed.

Changes and pre-tests

The die was surface-ground on the inside with a new counter-sinking of the holes and relieved by 1 mm approx. 10 mm into the die so that the new measurements were ø12 x 108 P96 mm. This corresponds to an effective press channel of 1:8, which generally corresponds to the ration that is used for pelletizing pure sawdust in the industry.

With a view to producing a new product and determining the required quantity of binding agent for R6, three pre-tests were carried out (R4A, R4B, R4C), in which, to 2/3 straw, 1/3 sawdust and 5% limestone, 3-5-6% rapeseed oil and 3-5-6% beet molasses, respectively, were added.

R4A: 3% rapeseed oil + 3% molasses + 9% water: 20-30% fines in the product. Capacity 500 kg/h, energy consumption 122 kWh/ton, overheating of die. Irregular pellet quality. Insufficient binding agent.

R4B: 6% rapeseed oil + 6% molasses + 9% water: 5-6% fines in product. Capacity 500 kg/h, energy consumption 68 kWh/ton, no overheating of die. Good pellet quality. Optimal quantity of binding agent.

R4C: 5% rapeseed oil + 5 % molasses + 9 % water: 10 % fines in product. Capacity 550 kg/h, energy consumption 83 kWh/ton. No overheating of die. Good pellet quality. Acceptable quantity of binding agent.

Recipe R6

This mixture consists of 57% wheat straw, 28% sawdust, 5% limestone, 5% rapeseed oil, 5% molasses.

The pre-tests showed that renovating the die had helped, but it was necessary and also an advantage to add rapeseed oil and molasses as binding agents to the mixtures of straw and sawdust.

The pre-tests also showed that adding water to the meal in the mixer was advantageous. 9.5% water was added and totally there was approx. 20% moisture in the product before pelletizing. The pellet press operated steadily without the die being overheated. The capacity was 650 kg/h. The pellets were short, but of a sound quality. It still looked as though the mixture lacked the binding attribute slightly. Fines in the product formed approx. 10%. Rate of evaporation was high during pelletizing. The capacity should perhaps have increased to 800-1000 kg/h, as this would have produced a better flow through the die and a better pellet quality.

R6 has shown that it was difficult to pelletize a mixture of straw and sawdust to which 5% limestone was added, even when relatively large quantities of rapeseed oil and molasses were added.

Recipe R7

This mixture consists of 58.3% grain screenings, 28.7% sawdust, 5.0% limestone, 3.0% rapeseed oil, 5.0% beet molasses.

Since grain screenings consist of hulls, chaff and underdeveloped grain kernels, it is an entirely different product to work with than straw. There is a slight amount of starch which is activated by steam and acts as a binding agent during pelletizing. Therefore two pre-tests were carried out prior to this test:

1. 5% rapeseed oil, 5% molasses + wetting of meal to 18-19% moisture. The test showed that there was too much oil and water - there was no resistance in the die. The pellets were well formed, but loose and non-cohesive after cooling. Oil and water quantities had to be reduced.

2. 0% rapeseed oil + 5% molasses + wetting of meal to 15% moisture. After a short run the die became too hot and there was a tendency towards clogging of the die. Adding water in the cascade mixer did not solve the problem. Oil had to be added.

Therefore, **R7** was produced with 3% rapeseed oil and 5% molasses wetted to approx. 15% moisture. The press ran smoothly and steadily. The best operational conditions were 850 kg/h and a meal temperature above 90 °C. Suitable quantities of oil and water were added to the meal in the mixer and there was a fitting proportionality between capacity and energy consumption of the press. The pellets were long and tough and after cooling they became firm and hard. Only 2.0% fine formation was measured and a hardness of 39 kg was registered.

This test showed that there was a big difference whether 1/3 sawdust was mixed with straw or with grain screenings. Compared to R6 the energy consumption in R7 decreased from 70 to 50 kWh/tons even though 2% less rapeseed oil was added. At the same time the pellet quality improved significantly in R7.

Recipe R8

This mixture consists of 59.0% grain screenings, 29.0% sunflower shells, 5% limestone, 2% rapeseed oil, 5% beet molasses.

Sunflower shells are remnants from pressing and cleaning of sunflower seeds. Sunflower shells contain a large amount of cellulose, but also a small quantity of oil which has a positive effect on the pelletizing of the mixture with grain screenings.

The experience gained during pelletizing of R7 was applied in R8. The amount of rapeseed oil added to the mixture was reduced to 2%. 2% molasses and 3.5% water were added to wet the meal to a moisture content of 14-15 %. This mixture was easy to pelletize. The press operated steadily and the capacity was increased to 1,500 kg/h with an energy consumption of 160-170 amp. Please note that the meal temperature was only 70 °C which was sufficient to ensure stable operation and good pellet quality. The pressure in the die was adequately high due to the relatively high capacity. The pellets

were long and tough, and after cooling they were firm and hard. Only 3.5% fines and 2.2 % fine formation were found in the product. The pellets had a slight tendency to crack which could indicate that there was more than enough moisture in the mixture before pelletizing.

No pre-test was carried out on this mixture, but this could very likely be produced either without oil or in a combination of a small quantity of oil and less molasses.

Recipe R9

This mixture consists of 59.0% grain screenings, 29.0% shea nut shells, 5.0% limestone, 2.0% rapeseed oil, 5.0% beet molasses.

Shea nut shells contain a large amount of cellulose and a small quantity of oil. Also in this test only 2% rapeseed oil was added and the meal was wetted to 15% moisture. This mixture was good for pelletizing. Best operation was achieved at 1,400-1,500 kg/h, meal temperature between 75-80 °C. Energy consumption was only 28 kWh/ton. The pellets were good, long and tough, and after cooling they became adequately durable. No pre-test was carried out on this mixture, but R9 could very likely be pelletized without both oil and molasses. Shea nut shells contain certain substances that enhance pelletability. Pelletizing of pure shea nut shells produces very good pellets and pellets without fines and with a KAHL hardness of 60-70 kg.

Recipe R10

This mixture consists of 88.0% grain screenings, 5.0% limestone, 2.0% rapeseed oil, 5.0% beet molasses.

Based on the experience gained from the previous tests with grain screenings, this test was carried out without a pre-test. The above-mentioned quantities of oil and molasses were considered suitable for pure grain screenings to which 5% limestone was added. The amount of limestone had a great effect on the mixture's pelletizing attributes. Limestone increased resistance in the die and contributed to a lower capacity without improving the pellets.

The mixture was suitable for pelletizing. There was a suitable content of moisture in the meal which was wetted to approx. 15% moisture. The press was stable and the pellets were good with a regular pellet length and suitable hardness after cooling. The capacity was 50% higher compared to R7 in which 1/3 of the grain screenings was replaced with sawdust. The energy consumption of both tests was the same.

Recipe R11

This mixture consists of 30.6% sawdust, 62.2% grain screenings, 3.0% limestone, 2.1% rapeseed oil, 2.1% beet molasses.

This test is a repetition of R7 in which the quantity of limestone was reduced to 3.0%. Since limestone has a negative effect on a mixture's pelletizing attributes, two tests were carried out:

1. 3% rapeseed oil without molasses: Lacked binding effect and poor pellet quality.

2. 3% rapeseed oil + 3% molasses: Stable operation, high capacity, good pellet quality.

Based on this, it was decided that R11 should be pelletized with approx. 2% rapeseed oil and 2% beet molasses, and the meal should be wetted to 14-15% moisture.

The pellet press was stable, capacity 1,100 kg/h, energy consumption 47 kWh/ton or the same as R7. Suitable quantities of oil and water were added to the meal in the mixer. Relatively high capacity produced the best pellet quality. The pellets were slightly short, fines formation was 8.3% and thus higher than R7. The cooled pellets were good with a fine formation of 4.7% and a hardness of 29 kg.

This test has shown that if the amount of limestone is reduced in this type of mixture, the amount of oil and molasses can also be reduced. The pellet quality was poorer than the quality of R7, but can be optimised in a commercial production.

Recipe R12

This mixture consists of 65.1% grain screenings, 31.9% shea nut shells, 3.0% limestone.

This mixture is a repetition of R9 in which the quantity of limestone was reduced to 3.0%. Based on the experience gained from R9, this mixture was pelletized without the addition of oil and molasses. Shea nut shells contain such a large amount of binding agent that it should be possible to produce a good pellet quality.

The test showed that with this mixture the press operated steadily and best at a capacity of 1,500 kg/h. The pellets were reasonably good, slightly irregular in length, but otherwise firm and hard after cooling. The high content of fines in the product, 10.4%, was primarily due to the formation of a good amount of short pellets. The reason could be a lack of binding agent, e.g. molasses.

R7-R12 all included grain screenings. This raw material was good for pelletizing purposes, either as a pure product or in a mixture with other raw materials. The composition of the mixture and quantity of additives have great influence on how much rapeseed oil and beet molasses need to be added in order to achieve a smooth operation of the pellet press and a good pellet quality.

TABLE 6-1

Test No.:	R1	R2	R3	R4	R5	R6
Biofuels
Wheat straw, %	98.9	98.0	95.5	63.8	60.7	57.0
Sawdust, %	-	-	-	31.4	30.0	28.0
Grain screenings, %	-	-	-	-	-	-
Shea nut shells, %	-	-	-	-	-	-
Sunflower shells, %	-	-	-	-	-	-
Additives
Aluminium hydroxide, $Al(OH)_3$, %	1.1	-	-	-	4.8	-
Kaolinite, $AL_2O_3\,2SiO_2 2H_2O$,%	-	2.0	-	-	-	-
Burnt lime, CaO, %	-	-	1.3	-	-	-
Limestone $(CaCO)_3$, %	-	-	-	4.8	-	5.0
Binding agents
Rapeseed oil, %	-	-	-	-	-	5.0
Beet molasses, %	-	-	3.2	-	4.5	5.0
Water added in mixer, %	4.0	5.9	6.0	11.0	7.0	9.5
Water added in cascade mixer, %	0	4.5	7.0	0	7.0	0
Grinding, mesh, etc., %	4.0	4.0	4.0	4.0	4.0	4.0
Pellet press, type	M5	M5	M12	M12	M12	M12
Die, type, ØxD, mm	12x80	12x80	12x110	12x110	12x110	12x108 P96
Meal temperature, ºC	90	90	99	95	95	95
Pellet temperature, ºC	94	93	96	96	96	91
Capacity, kg/h	400	410	600	400	400	650
Pellet press, amp	60	60	150	135	170	135
Pellet press, kWh/ton (nett)	50	49	91	114	164	70
Analysis
Fines in product, %	4.8	3.1	2.2	40	50	10.0
Formation of fines, %	5.1	5.0	2.5	34.2	12.2	4.7
Hardness, KAHL, kg	15.0	14.5	20.0	8.5	15.7	17.3
Bulk density, kg/m^3	600	590	675	550	620	600
Water in meal, %, (mixer)	13.5	15.0	15.6	19.9	15.9	19.6
Water in cooled pellets, %	12.8	14.3	12.2	7.7	6.0	10.3

TABLE 6-2

Test No.:	R7	R8	R9	R10	R11	R12
Biofuels						
Wheat straw, %	-	-	-	-	-	-
Sawdust, %	28.7	-	-	-	30.6	-
Grain screenings, %	58.3	59.0	59.0	88.0	62.2	65.1
Shea nut shells, %	-	-	29.0	-	-	31.9
Sunflower shells, %	-	29.0	-	-	-	-
Additives						
Aluminium hydroxide Al(OH)$_3$, %	-	-	-	-	-	-
Kaolinite, AL$_2$O$_3$ 2SiO$_2$2H$_2$O,%	-	-	-	-	-	-
Burnt lime, CaO, %	-	-	-	-	-	-
Limestone (CaCO)$_3$, %	5.0	5.0	5.0	5.0	3.0	3.0
Binding agents						
Rapeseed oil, %	3.0	2.0	2.0	2.0	2.1	-
Beet molasses, %	5.0	5.0	5.0	5.0	2.1	-
Water added in mixer, %	3.5	3.5	3.5	3.2	3.8	3.7
Water added in cascade mixer, %	0	0	0	0	0	0
Grinding, mesh, mm, %	4.0	4.0	4.0	4.0	4.0	4.0
Pellet press, type	M12	M12	M12	M12	M12	M12
Die, type, ØxD, mm	12x108 P96	12x108 P96	12x108 P96	12x108 P96	12x108 P96	12x108 P96
Meal temperature, °C	98	70	80	85	90	80
Pellet temperature, °C	96	90	90	90	93	88
Capacity, kg/h	850	1500	1450	1200	1100	1450
Pellet press, amp	130	165	125	130	145	135
Pellet press, kWh/ton (net)	50	42	28	36	47	32
Analyses						
Fines in product, %	5.0	3.5	4.1	4.0	8.3	10.4
Formation of fines, %	2.0	2.2	4.3	3.8	4.7	6.0
Hardness, KAHL, kg	39.0	34	27	33	29	27
Bulk density, kg/m^3	640	670	650	620	580	600
Water in meal, %, (mixer)	14.7	14.1	15.4	14.8	14.1	15.5
Water in cooled pellets, %	9.1	10.7	13.3	12.3	11.3	13.4

6.4. Pre-treatment of raw materials and mixtures for BYU

For the combustion tests at Brigham Young University (BYU) all the raw materials and the 12 pellet mixtures were ground to powder at the Biotechnological Institute's pilot plant.

A Champion hammer mill with a ø1.5 mm screen and a speed of 2,950 rpm, was used for grinding.

As a pre-test, 600 kg sawdust and 530 kg straw were ground and shipped. At BYU tests with these products showed that the particle size was suitable for the purpose.

The other raw materials and mixtures were ground the same way and bagged in paper bags for shipment.

The following quantities were shipped for BYU:

1,250 kg sawdust
1,350 kg wheat straw
790 kg grain screenings
675 kg sunflower shells
680 kg shea nut shells
680 kg sugar beet pulp
610 kg R1
630 kg R2
R3-R12: 35-40 kg of recipe
50 kg CaCO3
50 kg Al(OH)3

A screening analysis of the ground wheat straw was carried out on a vibrating sieve:

Particle size, µm	%
> 710	3.3
< 710 > 500	11.5
< 500 > 425	8.8
> 425 < 315	15.5
> 315 < 212	24.1
> 212 < 125	18.8
< 125	18.0

Screening analysis was only carried out on wheat straw in order to determine the degree of fines. Another particle size and distribution can be expected in the other raw materials in the various mixtures.

7. Market Analysis and Economy for Pellets

By Lars Nikolaisen, Danish Technological Institute

Since the early 1990's, the use of biofuel for heat and power generation has increased considerably in Denmark. This increase is due to the fact that biofuel is "green energy", fossil fuel is heavily taxed, fossil fuel prices are rising and there is no tax on biofuels except VAT. At the same time, investment subsidies have been granted to private consumers and plant owners installing biomass boilers. Up to 2003, the market for wood pellets has only been related to private consumers, district heating plants and a few industries. From 2003, the utility boiler "Avedøre 2" will consume 300,000 tons of wood pellets annually and "Amagerværket 2" will consume 130,000 tons of straw pellets annually.

7.1. Prices

The prices of fossil energy change rapidly and each quarter the prices show remarkable leaps. The variation in biofuel prices increases and the statistics regarding fuel prices from the Danish District Heating Association clearly show that within the recorded twelve-year period there are no signs that the oil prices effect the biomass prices. An independent market for biofuels has been established where primarily the production costs, but also the supply and demand, adjust the prices. There is a slightly descending tendency in the current biofuel prices, and in the fixed biofuel prices there is a more significant fall, as the inflation must be deducted when the prices of biofuels from the preceding years are compared. However, the fossil energy price can very much be considered as a political barometer.

For private consumers the changes in prices for fossil fuel and wood pellets are the same as for district heating plants, but the price level is up to 50% higher. Figure 1 shows that during a period of 12 years the prices corrected for inflation have not increased, but the prices of fossil fuel often change due to international political instability.
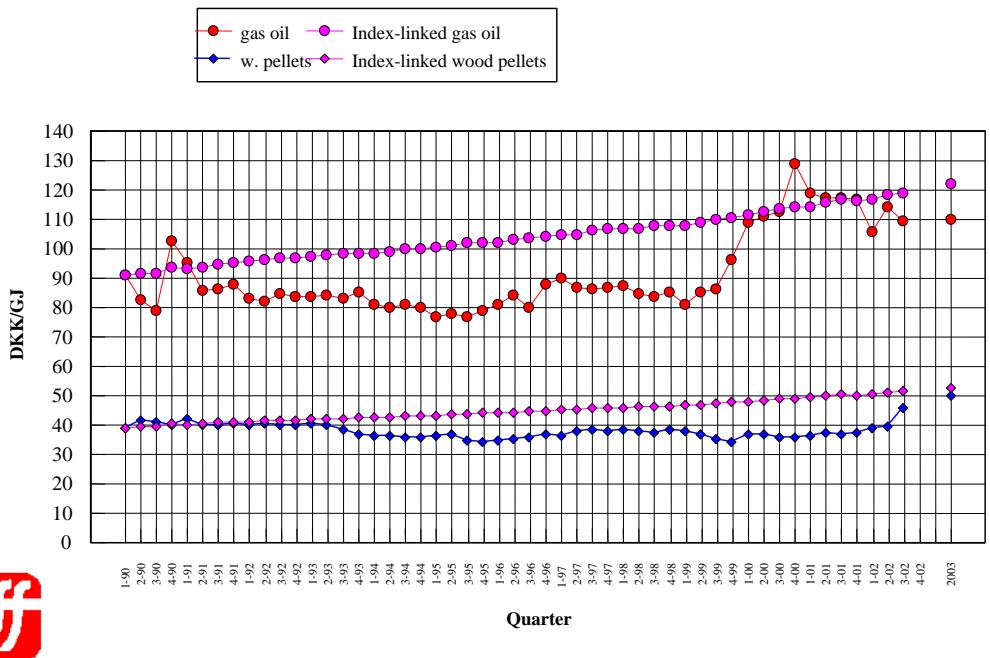
Figure 7-1. Statistics covering 12 years of fuel prices in the Danish district heating sector for light oil and wood pellets. Note the indexation of the prices. Prices are exclusive of VAT. Reference: Quarterly price statistics, Danish District Heating Association.

During the period 2000-2002 the price of wood pellets increased rapidly up to 40-50% - first for private consumers, later for district heating plants. In October 2002, 3 tons of pellets for a private consumer delivered by truck as bulk cost 1,500 DKK/ton exclusive of VAT, in total 1,875 DKK/ton. An important reason for the price rise of 40-50% is that the price of sawdust from the Danish wood processing industry has increased over a few years from almost 0 to more than 500 DKK/ton exclusive of transport. Another factor is that the pellet manufacturers are extending the pellet storage in order to meet the increased demand in the winter. In general, it is "seller's market" with shortage of pellets in February and March.

Wood pellet prices exclusive of transport in DKK/ton
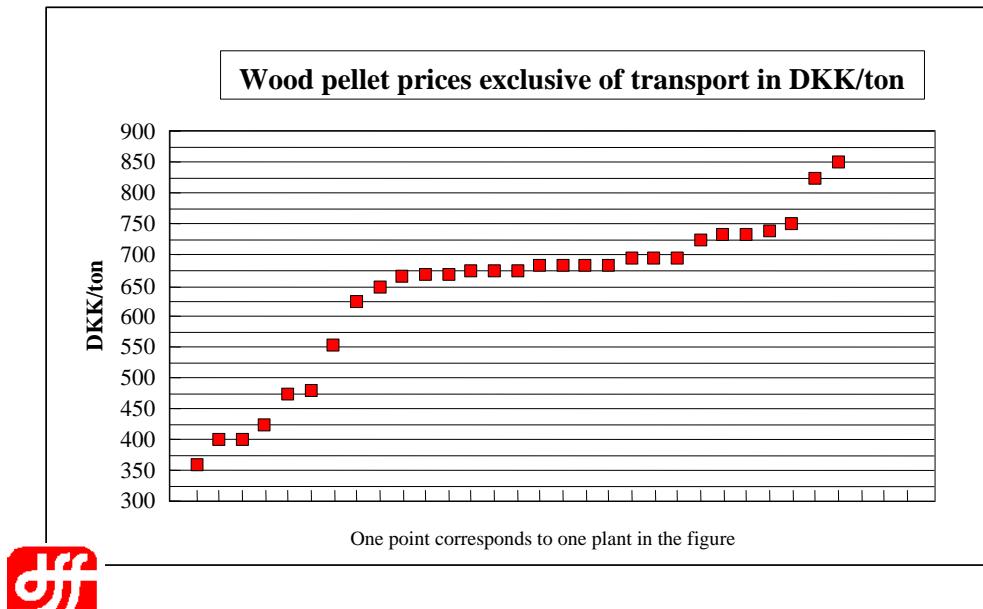
Figure 7-2. The price span for 29 district heating plants using wood pellets ultimo 2001. The span is from 360 DKK/ton to 850 DKK/ton. The very cheap prices are long-term contracts or other types of waste wood. The prices are exclusive of VAT and transport to the plant. Reference: Danish District Heating Association.

Wood pellet prices exclusive of transport in DKK/ton
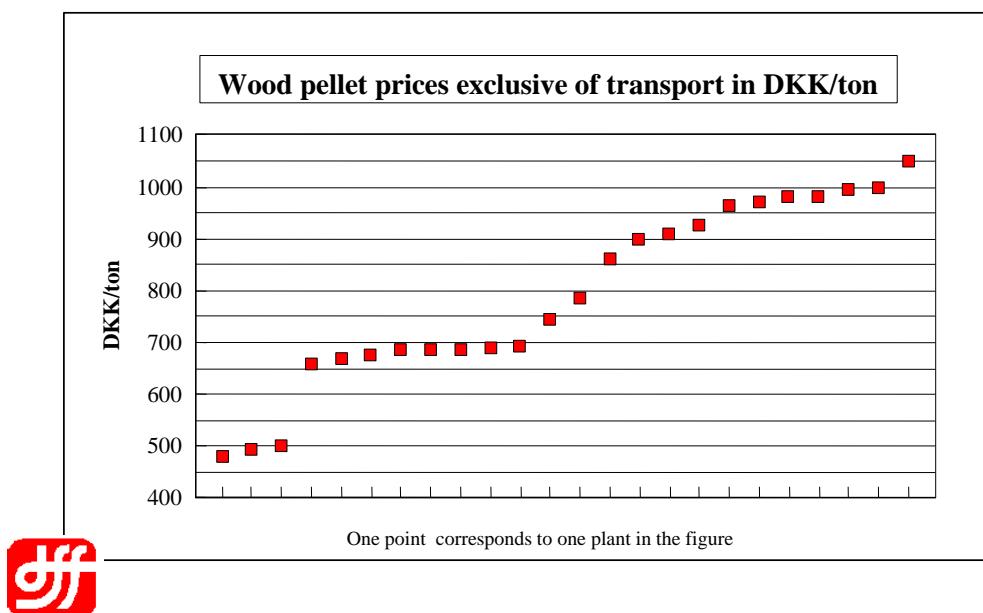
Figure 7-3. The price span for 25 district heating plants using wood pellets, in the middle of 2002. The span is from 470 DKK/ton to 1,050 DKK/ton. The very cheap prices are long-term contracts or other types of waste wood. The prices are exclusive of VAT and transport to the plant. Reference: Danish District Heating Association.

Although the production costs for imported pellets differ from Danish pellets due to different costs of raw materials, wages, transport etc., the price for the end-user is more or less the same. There is a discount on some imported pellets, 100-200 DKK/ton.

However, some of the imported pellets have a slagging tendency meaning that the raw material has a different composition than Danish pellets which are produced on sawdust. Analyses of the slag indicate that the raw material is contaminated with sand and soil.

7.2. Consumption and import

Denmark is net importer of biofuels and imports trunks as well as wood chips and wood pellets. In 1998, Denmark's import from Germany of shavings (dry, industrial waste wood) etc. reached 164,000 tons with an upward tendency. Of this quantity an unknown amount of tons are used for pellet production, and the rest is used for chipboard production. Denmark imports wood pellets from the Baltic countries, Sweden and Canada (and small quantities from Finland and Poland). Investments in the Swedish wood pellet industry have increased and today the production capacity reaches more than the approx. 700,000 tons per year presently produced. This means that an increased export is possible.

Wood pellets in 1,000 tons	1998	1999	2000	2001
Annual consumption in Denmark	**172**	**180**	**250**	**300**
Production in Denmark	129	140	150	175
Import from Canada	(5)		0	0
Import from Sweden	13	25	40	25
Import from Germany	0	0	0	0
Import from the Baltic States	(25)		60	100

Table 7-1. The Danish turnover of wood pellets 1998-2001 in 1,000 tons. The numbers are approximate, as they are not easy to verify at the highly competitive market. The numbers in brackets are uncertain. The consumption in 2002 is expected to be 320-330,000 tons, but the production in Denmark on sawdust will probably not exceed 175,000 tons due to lack of and high prices of sawdust from the Danish wood processing industry. The figures are collected from pellet producers, importers etc., and are higher compared to the statistics from the Danish Energy Agency.

Utility companies

The utility company, Elsam, in Western Denmark has no power plants using pellets for power generation. In Eastern Denmark, Energi E2 is rebuilding "Amagerværket, boiler 2" from being coal-fired to being fired with straw pellets. The consumption is expected to be 130,000 tons/year from 2003. "Avedøreværket, boiler 2" is as a multi-fuel boiler ready to burn 130,000 tons of wood pellets a year from ultimo 2002. The straw pellets and 180,000 tons of wood pellets will be produced at Junckers Industries in Køge by a recently built pellet factory. The 180,000 tons of wood pellets are produced with sawdust from Junckers Industries, and will therefore not interfere with the Danish market for raw materials. The remaining 120,000 tons of wood pellets have to be imported.

District heating plants

In Denmark, approximately 40 district heating plants partly use wood pellets. Their annual consumption of about 110,000 tons is used for hot water production for district heating purposes. However, no power is generated. The boilers were originally coal-fired with travelling grate or drop-tube and were built in the early 1980's where coal was cheap and oil became more and more expensive. In average, the boiler size is 6 MW. In 1982 and 1986, the Danish government imposed tax on coal, and wood pellets became competitive as almost no changes of the coal-fired boilers was necessary in order to burn wood pellets. The wood pellet consumption increased over 5 years from 0 to 100,000 tons/year.

Wood pellets on DH plants
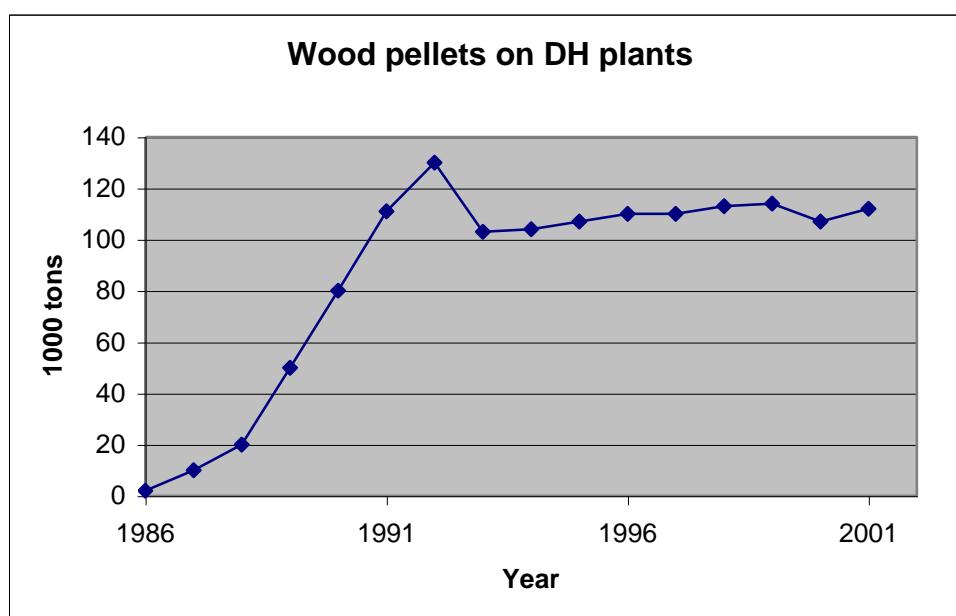
Figure 7-4. Wood pellet consumption at 40 Danish district heating plants. Reference: Danish Energy Agency.

Industrial boilers and boilers in public buildings

Only small quantities of wood pellets are consumed by the industry, schools, public swimming pools, etc., and the boiler sizes vary from 100 kW to 1,000 kW. The industry pays limited tax on fossil fuel which is why the conversion to biofuels is very slow in the industrial sector in Denmark. However, schools and other public buildings have to pay energy tax. Many schools and public buildings in rural areas install new pellet boilers and use the oil-fired boilers for peak load and as stand by boilers.

Wood pellets in industries & public buildings
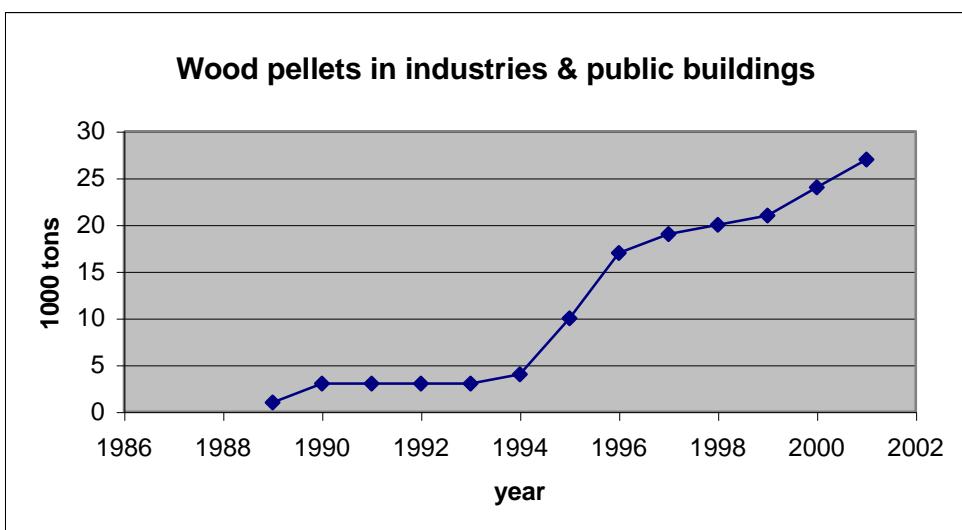
Figure 7-5. Wood pellet consumption in industries and public buildings. Reference: Danish Energy Agency.

Household boilers

In the 1980's no wood pellet-fired boilers were found on the Danish market and only a few consumers used wood pellets in their old coal-fired boilers as pellets were hardly for sale. In the beginning of the 1990's some manufacturers started to develop automatic boilers and burners especially designed for 8-12 mm wood pellets. The manufacturers faced several problems: Risk of backfire, high CO emission, low efficiency, low summer load performance, problematic access to cleaning the heat surfaces of the boiler, etc.

In 1995, a government subsidy scheme for automatic biofuel boilers up to 200 kW was introduced, and type testing became of immediate interest to the manufacturers. As a condition for subsidies being granted, the Danish Energy Agency required that the boiler should be type approved, thereby complying with a wide range of requirements regarding emission and energy utilisation. Type testing is carried out by the Test Laboratory for Small Biofuel Boilers at the Danish Technological Institute in accordance with guidelines for testing in order to achieve a type approval. The guidelines were prepared on the basis of EN 303-5. The requirements are established in a joint collaboration between the manufacturers of biofuel boilers, the Test Laboratory for Small Biofuel Boilers, the Danish Energy Agency and the Danish Environmental Protection Agency.

The type approval scheme has - to a large extent - effected the quality, the safety and the efficiency of small biofuel boilers. Since 1995, a large number of boilers have been installed, and about 11,000 type approved boilers and 8-10,000 other boilers are now in operation in Denmark for household heating.

Wood pellets in private households
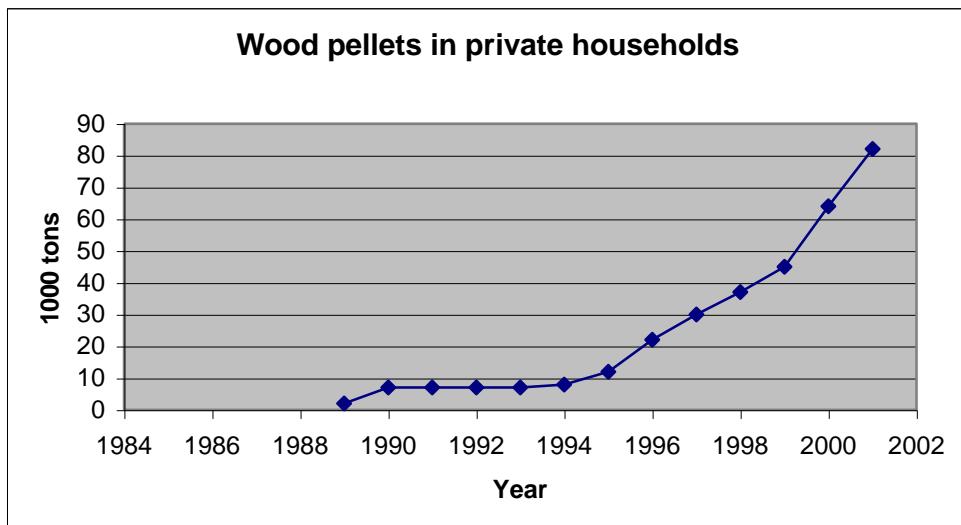

Figure 7-6. Wood pellet consumption in household boilers. Note the steep curve from 1995 when a government subsidy scheme was introduced. The figures are statistics from the Danish Energy Agency, but they are probably too low. In 2001, 20,000 boilers were installed, and with an annual consumption of 6 tons/year the figure in 2001 should be 120,000 tons.

The government subsidies for installation of biofuel boilers stopped in 2001 and subsidies for type testing stopped in 2002. However, type approval of boilers paid by the manufacturers will continue.

7.3. Market trends 2003 - 2005

The steep curve for pellet consumption in private households will probably stay at the same level due to increased pellet prices and increased need for investments. In 1995, an investment in a type approved pellet boiler was subsidised with 30%, in 2002 the subsidy is 0. The pellet price has doubled and the price of light oil has increased 20% in the same period. In 1995, the simple payback time for a new pellet boiler was about 4 years, in 2002 it is about 11 years. This means that a very few new pellet boilers will be installed compared to the late 1990's. A way to reduce the size of the investment is to buy a boiler or a stoker which is not type approved. The risk of buying this type of equipment is to get a heating system with possibility of backfire, bad efficiency, bad summer performance and high emissions to the atmosphere. Due to the increasing pellet prices, many consumers who have invested in a pellet boiler try to use cheaper biofuels such as grain, residues from plant oil production (rape, shea, sunflower, olive), etc. The risk is to get a biofuel with serious slagging tendency, high fouling on heat surfaces, high ash content and high emissions to the atmosphere.

In the district heating sector most of the 40 boilers using wood pellets are approximately 20 years old and will soon be ready for scrapping. With the actual price level of wood pellets many district heating plants try to introduce other, cheaper biofuels such as bark, wood chips, grain screenings, residues from plant oil production etc, and many of the old travelling grates can burn this type of fuel. Investing in a multi-fuel boiler is another possibility. It is anticipated that the consumption of wood pellets in the 40 plants will decrease with 30-50,000 tons/year in a few years.

A new wood pellet consumer in the district heating sector could be the 82 combined heat and power plants at which natural gas engines and generators are installed. Due to high gas prices, many plants have planned to substitute 30-40% of the heat production with a wood pellet boiler. However, increased pellet prices and a government change in the taxation on the gas making it cheaper to produce hot water for district heating on the gas engine have turned this planned conversion into a less attractive investment.

Due to the vast consumption of wood pellets at "Avedøre 2", the consumption in Denmark will almost double in 2003 and ahead. The district heating sector will reduce the consumption of wood pellets and the private households will try to find alternative and cheaper biofuels. If the slagging problems for some imported pellets are solved and the consumers' confidence in this type of pellet is re-established, the imported wood pellets might be very competitive to Danish wood pellets produced on expensive raw materials.

The biofuel pellets developed in this project point in a new direction: By mixing different raw materials and additives it is possible to develop a pellet with well-defined characteristics such as:

- No slagging tendency (except at air nozzles)
- High ash content (like coal)
- Some dust fouling on heat surfaces
- Price competitiveness to wood pellets.

Not all small boilers for households are able to burn this type of pellets, but some of them are. Larger boilers from 100 kW and upwards which are equipped with an ash screw and maintained daily can burn this type of biofuel pellets.

7.4. Economy for biofuel pellets

Pelletization means costs and energy consumption compared to the energy utilization of more unprocessed biomass. Convenience, homogeneity and high density are some of the advantages that can justify these extra costs in small-scale boilers. For larger boilers pelletization can - in some cases - make co-firing with other fuels possible at low investment costs compared to a new biomass system.

Pelletization makes it possible to transport biomass over larger distances or use biomass where it seems impossible due to logistic problems like the use of straw pellets at "Amagerværket". It was not possible to get permission by the authorities to transport straw bales on truck through central Copenhagen. The result is that the straw is pelletized at Junckers Industries 50 km away and shipped to Copenhagen.

Raw material costs

Raw material prices depend on the market demand for the raw material considered. If there are no buyers for biomass produced as waste by an industry, the value is 0 or even negative. This could initiate a production of bio pellets and justify relatively high transport costs. In the middle of the 1990's, the annual consumption of sawdust was smaller than the amount of sawdust on the market. The prices used for the calculations are the actual market prices for larger amounts including medium distance transport in Denmark. The amount considered is an annual pellet production of 60,000 tons/year. This amount can be produced on one production line with a capacity of 10 tons/hour in 6,000 hours/year. Prices are collected from the raw material suppliers.

Raw material	Price in DKK/ton	Annual tons in DK	Remarks
Straw bales	400	>500,000	Big bales
Sawdust	550	170,000	Meal
Grain screenings	100	Up to 100,000	Meal
Sunflower shells	650	10 - 20,000	Pellets
Shea nut shells	450	Unknown	Meal

Table 7-2. Raw materials used for the 12 recipes. The prices are exclusive of transport (170 DKK/ton) to the pellet manufacturer and the expected annual amounts in Denmark. The prices are for purchase of large annual amounts. The market survey for raw materials is discussed in chapter 5.

Additive costs

The deslagging additives used are based on aluminium and calcium. If you want to make a proper pellet with a low amount of fines and a good strength, the binding agent should be molasses. As lubricant in the die rapeoil was used.

Additive	Price in DKK/ton	Remarks
Aluminium hydroxide	1,800	Meal
Kaolinite	1,500	Meal
Calcium oxide	900	Meal, caustic
Limestone	250	Meal
Molasses	600	Fluid
Rapeoil	3,000	Fluctuating prices

Table 7-3. Additives used for the 12 recipes. The prices used in the calculation are for purchase of large amounts delivered as bulk/fluid in trucks inclusive of medium distance transport (100-150 km). Rapeoil is a very expensive additive.

Material costs for the 12 recipes

Recipe	Price in DKK/ton	Recipe	Price in DKK/ton
R1	414	R7	498
R2	422	R8	500
R3	411	R9	474
R4	495	R10	340
R5	672	R11	470
R6	622	R12	381

Table 7-4. Prices of raw materials and additives for the 12 recipes. All materials are "as received" meaning that straw is still in big bales. The water content is 9-15%. The price of dry sawdust is 720 DKK/ton and the price of chipped and dried logs is 338 DKK/ton for comparison. The figures are used in the final calculation of pellet prices in table 7-7. The detailed calculations are shown in Appendix 4.

Capital costs for pelletization

The capital costs for pelletization are calculated for a production line with a capacity of 10 tons/hour. For the R1-R6 recipes containing straw it is necessary to add a straw scarifier to the plant. The investments regarding R1-R12 production are compared to production of wood pellets based on sawdust and on chipped and dried logs.

Investment in 1,000 DKK	Without scarifier	With scarifier	With drying
Straw scarifier	0	1,900	0
Hammer mill	3,000	3,000	3,000
Pellet press	7,000	7,000	7,000
Cooling section	1,600	1,600	1,600
Fire protection	700	700	700
Steel construction	2,500	2,500	2,500
Assembly	3,500	3,500	3,500
Electricity	3,000	3,000	3,000
Conveyer, sieve, etc	5,000	5,000	5,000
Drying line + chipper	0	0	15,000
Buildings	22,000	22,000	24,000
Total investment	**48,300**	**50,200**	**65,300**

Table 7-5. Estimated investment costs for pellet production with or without straw scarifier and with drying of chipped logs for comparison. The annual production capacity is 60,000 tons.

Capital costs per tons of pellets produced depend on the number of effective production hours. The calculations are based on 6,000 production hours per year.

The depreciation period is 7 years for machinery investments and 15 years for building investments. The annual interest is 7%. VAT is not included unless specified.

Variable costs for pelletization

Variable costs include maintenance, labour, electricity, administration, profit, transportation, etc. Costs of transport and distribution depend on the system used, tonnes per load and the distance.

DKK/tons	Without scarifier	With scarifier	With drying
Capital costs			
Machinery depreciation	63	67	98
Building depreciation	24	24	27
Interest (average)	31	32	42
Total capital	**118**	**124**	**167**
Variable costs			
Wages	55	55	76
Spare parts	30	32	40
Electricity	70	75	95
Transport to distributor	70	70	70
Insurance, water, etc.	10	10	15
Administration and profit	150	150	150
Transport to end-user	100	100	100
Fuel for drying	0	0	100
Fuel for steam	20	20	20
Interest pellet storage	25	25	25
Total variable	**530**	**537**	**691**

Table 7-6. Estimated pellet production costs exclusive of raw material costs. The calculation including straw scarifier is used for R1- R6, without scarifier for R7-R12 and wood pellets on sawdust. The drying line is used for calculation of wood pellets made of chipped and dried logs. In general, the price settings are conservative.

Pellet price for R1 - R12

Total costs	DKK/ton	GJ/tons	DKK/GJ
R1	1,075	15.30	70.25
R2	1,083	15.10	71.71
R3	1,072	15.20	70.51
R4	1,156	15.40	75.05
R5	1,333	15.20	87.68
R6	1,283	16.20	79.19
R7	1,146	15.30	74.90
R8	1,148	15.50	74.04
R9	1,122	14.70	76.34
R10	988	14.30	69.10
R11	1,118	15.60	71.68
R12	1,029	14.80	69.56
Pellets of sawdust	1,368	17.28	79.17
Pellets of dried logs	1,196	17.28	69.20
Market price, district heating	*1,000*	*17.28*	*57.87*
Market price, private consumer	*1,500*	*17.28*	*86.81*

Table 7-7. The production price for the 12 recipes and wood pellets in tons and per energy unit compared to the wood pellet market prices for district heating plants and private consumers. All prices are exclusive of VAT.

7.4.   Conclusions

During the last 10 years, the Danish wood pellet market has been very turbulent: From a consumption of 0 in 1980 to 300,000 tons/year in 2001. The consumers are district heating plants, industries, public buildings, private households and - from 2003 - utility companies. The rapidly growing demand has challenged the pellet manufacturers regarding access to raw materials, production capacity, storage facilities and distribution systems. Pellet shortage has lead to import from the Baltic countries and overseas, and the pellet price has increased.

The biofuel pellets developed in this project point in a new direction: By mixing different raw materials and additives, it is possible to develop a pellet with well-defined characteristics such as:

- No slagging tendency (except at air nozzles)
- High ash content (like coal)
- Some dust fouling on heat surfaces
- Price competitive to wood pellets

The production price of most of the 12 recipes is competitive to the calculated production price of wood pellets. Note that this is a test production which means that expensive raw materials such as rapeoil were used in some tests. If rapeoil is omitted, the price will be about 100 DKK/tons lower. The calculation shows that it is possible to develop good biofuel pellets out of waste materials. In general, the price settings, investments, depreciation, etc. are conservative in this calculation. This means that a more detailed calculation for commercial production would generally result in lower prices.

8.   Combustion Tests with 12 Mixtures

By Torben Nørgaard Jensen, Danish Technological Institute

8.1.   Test rig and operational conditions

The combustion tests were carried out at a test rig in the Energy Laboratory at Danish Technological Institute in Aarhus, Denmark.

At the test rig it is possible to control the return temperature of the water and it is possible to adjust the water flow to a requested level. The draught in the chimney is also adjustable.

The aim of all the tests was to achieve a return temperature of approx. 60 °C. The water flow was adjusted so the water temperature increased 10-20 °C. The draught was adjusted according to the boiler manufacturer's instructions.

The tests were carried out at nominal heat output.

Boiler settings

The boiler settings were the same during all the tests. The PLC controller was set in order to obtain a high excess air ratio (approx. 1.5 - see Figure 8-1) in the flue gas and the step grate was set to move frequently. An exception was the test with wood pellets during which the step grate did not move as frequently as in the other tests due to much lower ash content. Both initiatives were taken in order to make the boiler being able to handle the difficult fuels.

The actual settings, as to the step grate, might cause unburned fuel in the ash because there is a risk that the fuel will be pushed into the ash box before it is completely burned out. It may also have a bad influence on the combustion quality regarding the CO content in the flue gas because there is a risk that CO peaks will occur when the step grate moves.

However, this is estimated to be of much less importance than the slag problem which is the main issue of this project. The main purpose is to examine if the boiler is capable of handling the fuels as regards to the ash and slag.

If the most optimal settings should be found for every test, in some cases it would be necessary to adjust throughout most of the test because of the enertia of the system. This would make the comparison between the fuels difficult.

**Excess air related to O$_2$ % and CO$_2$ %
in dry flue gas (straw/wood)**
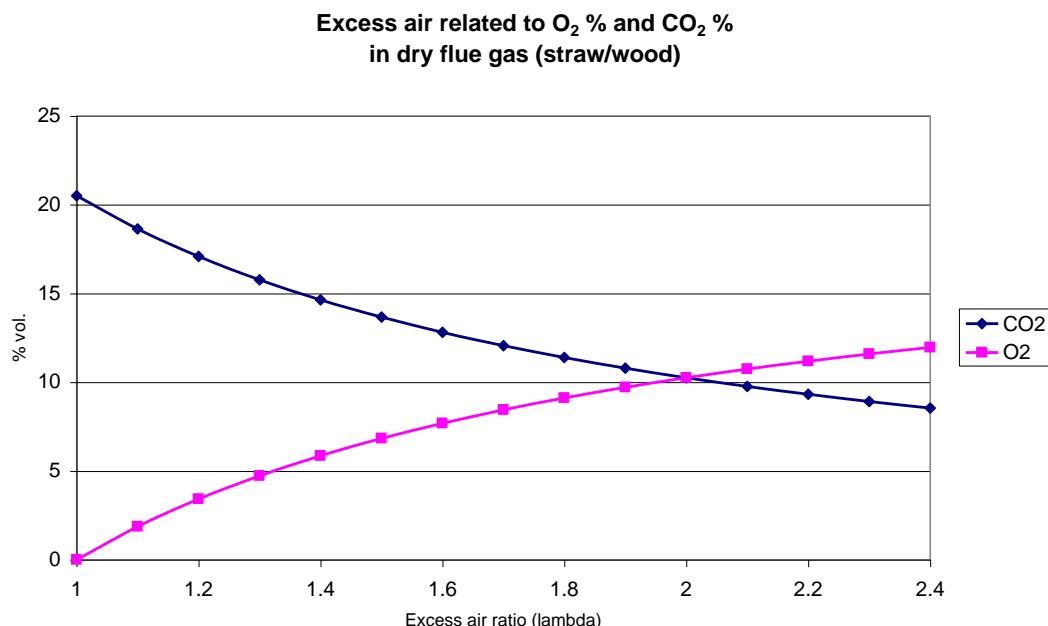
*Figure 8-**Fejl! Ukendt argument for parameter.**. Excess air in the flue gas. Burning biofuel needs a
relatively high
excess air ratio between 1,5 and 1,7*

8.2. Test procedure - measurement program

The tests were carried out according to the following program:

- Each fuel was tested for 72 hours at nominal load
- Wood pellets were tested one day at nominal load
- Boiler and flue gas tubes were cleaned before each test.

During each test the following were carried out:

- Sampling of ash
- Sampling of dust in flue gas tubes
- Efficiency for the total test period was measured
- Dust emission was measured
- Flame and slag temperatures were continuously measured (see Picture 8-1)
- CO$_2$, CO, NO$_x$ and SO$_2$ contents in the flue gas were continuously measured
- Furthermore, ambient temperature, flue gas temperature, draught, water
  temperatures and water flow were continuously measured

67
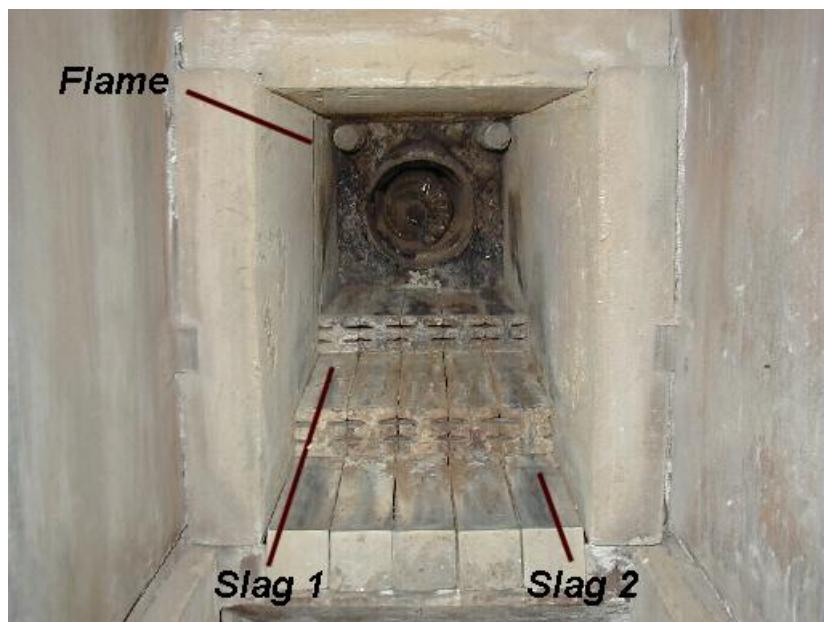
*Picture 8-**Fejl! Ukendt argument for parameter.**. Points for temperature measurements in the combustion chamber.*

8.3.   Accomplishment of and reporting the tests

All the tests were based on the following:

- There were no interruptions during the test as to adjustment, removal of slag etc. The boiler door was not opened until the test was completed.

- After 24 hours of testing, a sample of dust was taken from one flue gas tube.

- The measuring equipment was cleaned and calibrated before starting the test and after 48 hours.

During the test, the performance was evaluated. The following items were evaluated and commented on in all the tests:

Combustion quality: The evaluation of the combustion quality is related to the general CO content and the height of the CO peaks (see below).

Slag formation: Quantity, size and consistency of the slag is evaluated. Furthermore, it is evaluated if there are problems regarding fixed slag.

Dust fouling: Regards to fouling in combustion chamber and flue gas tubes. Fouling makes the flue gas temperature increase which makes the efficiency decrease.

Evaluation: General impression - what is positive and what is negative.
All tests were accomplished in the same way. The evaluations mentioned regard to the same items for each test, the graphs have the same graduation on both axes in all the tests, the data tables content the same data for each test and the photos are taken at the same time showing the same objects.

As previously mentioned, the CO content in the flue gas is applied in order to evaluate the combustion quality. The CO content is a good indicator for the efficiency of the combustion. If the CO content is low, the content of other combustible gases in the flue gas is low, too. In other words – the lower CO content, the better combustion.

During the tests, the CO content was evaluated according to the limits below.

CO content	Low	Medium	High
CO at 10% O_2 [ppm]	<300	300-700	700<

*Table 8-**Fejl! Ukendt argument for parameter.**. Limits for evaluating of combustion quality.*

Please note that all emission values are referred to dry flue gas at 10% O_2.

Please also note that:

- In the tests with R1-R3 the boiler was stopped manually because of serious slag problems. In these tests the efficiency was not calculated.

- The test with R4 stopped during the third night of testing. The precise test duration is therefore unknown which is why the efficiency was not calculated.

8.4. Explanation of words

Ash screw   Screw that automatically removes the ash from the ash box.

Crumbly ash   Ash that does not melt together and is easily removed by the ash screw.

Draught   The partial vacuum in the chimney.

Excess air   Surplus air in the flue gas that is necessary for a complete combustion.

Fixed slag   Slag that stays in the combustion chamber and is fixed either at the refractory in the combustion chamber or at the air nozzles.

Fuel hopper   Hermetic container for fuel storage from where the fuel is screwed into the combustion chamber.

PLC   Programmable Logic Controller.

Screw stoker   Screw that moves the fuel from the fuel hopper to the combustion chamber.

Slag   Ash that melts together.

Step grate   Grate in the bottom of the combustion chamber divided into three steps of which the second step is moveable.

8.5. Recipes

Recipe	Pellet diameter	Biofuel 1	Biofuel 2	Anti-slagging additive	Binding agent	Lubricant
Wood pellets	8 mm	1/1 sawdust				
R1	12 mm	1/1 straw		1% aluminium hydroxide		
R2	12 mm	1/1 straw		2% kaolinite		
R3	12 mm	1/1 straw		1% calcium oxide	3% molasses	
R4	12 mm	1/3 sawdust	2/3 straw	5% limestone		
R5	12 mm	1/3 sawdust	2/3 straw	5% aluminium hydroxide	5% molasses	
R6	12 mm	1/3 sawdust	2/3 straw	5% limestone	5% molasses	5% rapeoil
R7	12 mm	1/3 sawdust	2/3 grain screenings	5% limestone	5% molasses	3% rapeoil
R8	12 mm	1/3 sunflower shells	2/3 grain screenings	5% limestone	5% molasses	2% rapeoil
R9	12 mm	1/3 shea nut shells	2/3 grain screenings	5% limestone	5% molasses	2% rapeoil
R10	12 mm	1/1 grain screenings		5% limestone	5% molasses	2% rapeoil
R11	12 mm	1/3 sawdust	2/3 grain screenings	3% limestone	2% molasses	2% rapeoil
R12	12 mm	1/3 shea nut shells	2/3 grain screenings	3% limestone		

Table 8-2. Recipes

8.6. Boiler

Criteria for selection of boiler

The boiler was selected on the background of two previous projects: "Alternative biobrændslers anvendelighed i små fyringsanlæg fra 20 kW til 250 kW", ENS j.nr. 51161/97-0034, during which 14 biofuels were tested in 5 different boilers and "Energi-afgrødeprogrammet 1997-2000, Brændselsanalyser og fyringsforsøg", J.nr. 93S-2466-Å97-0125, Direktoratet for FødevareErhverv and J.nr. 51161/97-0039, Energistyrelsen, during which 20 biofuels were tested in one boiler.

The first project proved that the selected boiler, a Reka with a nominal heat output of approx. 30 kW, was the best mainly because of the fact that the boiler was equipped with a small step grate.

On this background, the boiler was also used in the second project. This project confirmed that a step grate is necessary when a fuel contains a large quantity of ash and has a slagging tendency.

Despite of the fact that the step grate makes the boiler special compared to the other small boilers on the market, the boiler was selected for this project. When know-how within this field has increased considerably, it will be obvious to carry out examinations of ordinary boilers' ability to use these kinds of fuels.

Boiler - construction and mode of operation

REKA HKRST-FSK 30 (nominal heat output 30 kW)

The boiler is a fully automatic boiler. It consists of a stoker, a boiler and a boiler base. The stoker consists of a fuel hopper, movable scrapers at the bottom of the fuel hopper and a screw stoker.

The boiler is a welded boiler made of steel plates with two flue gas passes each consisting of 8 tubes. The boiler base consists of a step grate and a combustion air fan.

The fuel is transported via a screw stoker from the fuel hopper to the combustion chamber in which the combustion takes place. Primary air is supplied through nozzles in the step grate.

Secondary air is supplied via two nozzles placed at the top of the combustion chamber. The combustion chamber is lined with refractory.

The boiler is equipped with a PLC controller for controlling the on-off phase for the screw stoker. The PLC unit regulates the fuel supply by measuring the exess air in the flue gas. If the exess air rate is too high, the fuel supply is increased and vice versa.

The combustion air fan is not adjustable which is why there is only one setting for the heat output. Therefore, the requested temperature is achieved by on/off regulation controlled by the boiler thermostat.
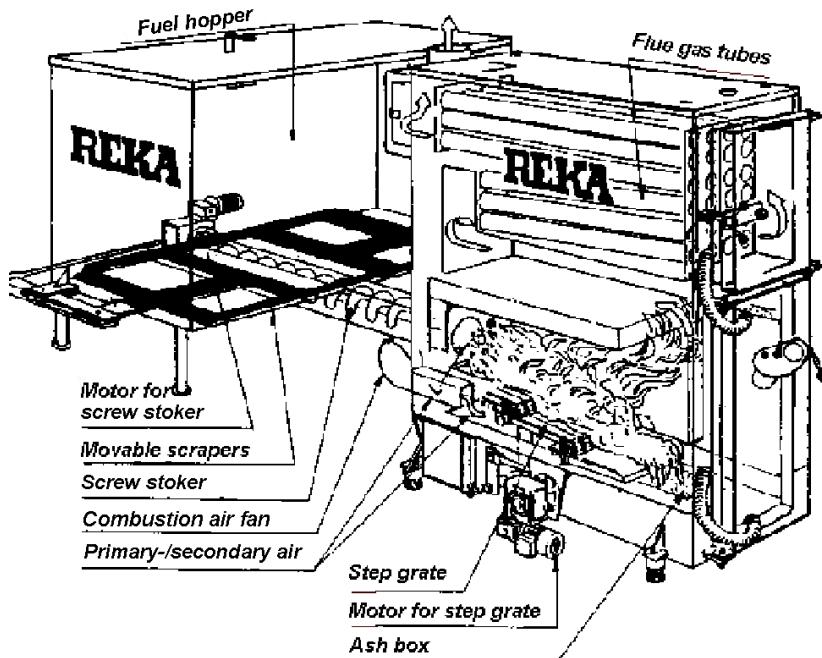

Figure 8-2. Sketch of the boiler. In addition, the boiler is equipped with an ash removal system. The ash is removed from the ash box in front of the boiler to an air proof box at the side by an ash screw.

8.7. Comparison of test results

General evaluation

Wood pellets
No problems. Constantly very good combustion, steady heat output and flue gas temperature. No slag, neither fixed in the combustion chamber, nor in the ash. No considerable fouling in combustion chamber and flue gas tubes. The pellet quality was high, i.e. the pellets did not emit dust when filled into the fuel hopper.

R6, R7, R8, R11 and R12
No problems with slag in the ash (except R12), but a considerable formation of fixed slag at the air nozzles. The pellet quality was high, i.e. the pellets did not emit dust when filled into the fuel hopper. The high quality also had a positive effect on the combustion quality. Combustion chamber and flue gas tubes were heavily fouled with dust.

The fuels are probably useful in most small boilers, but using them will require a lot of work regarding frequent cleaning of combustion chamber and flue gas tubes.

R9 and R10
Like R6, R7, R8, R11 and R12 except from some tendency of slag in the ash. It did not cause problems in the current boiler because the slag was crumbly, but it might cause problems in less robust and simpler boilers. There was serious formation of fixed slag at the air nozzles.

R4 and R5
No problems regarding slag in the ash, but a serious formation of fixed slag at the air nozzles. Furthermore, combustion chamber and the flue gas tubes were very heavily fouled. The pellets emitted a lot of dust when filled into the fuel hopper due to the poor pellet quality.

R1, R2 and R3
All the tests were stopped during the first two days due to huge slag problems - the combustion chamber was completely filled with slag. The combustion chamber and the flue gas tubes were very heavily fouled and the pellet quality was poor.

In Table 8-3 the fuels are evaluated according to parameters estimated to be the most important in order to classify the fuels. At each parameter the fuels have obtained a mark from 1 to 10. 1 is best and 10 is poorest. In the column "Total" the overall marks for each fuel are shown. They have been calculated as the average of the evaluated parameters.

It should be noted that the evaluation is subjective and that these comparisons are difficult to make as most of the parameters are evaluated by visual observation. However, it is estimated that the marks are very useful for evaluation if attention is given to the fact that they are only normative.

	Total	Slag in the ash	Fixed slag	Dust fouling	Combustion quality	Pellet quality
Wood pellets	1	1	1	1	1	1
R1	9	10	-	10	10	6
R2	8	10	-	10	6	7
R3	9	10	10	10	10	5
R4	7	2	10	8	4	10
R5	6	2	10	10	2	7
R6	4	2	9	3	3	3
R7	4	2	9	4	2	2
R8	4	2	9	4	2	2
R9	5	4	10	4	2	3
R10	5	4	10	5	2	2
R11	4	2	8	2	2	4
R12	4	6	8	2	1	2

Table 8-3: No marks were given to R1-R2 in "fixed slag" as the test periods were too short for evaluating this parameter. The evaluation clearly indicates that wood pellets are in a class by themselves just as it is very clear that R1, R2 and R3 are in a class by themselves, but at the other end of the scale. R4 and R5 are evaluated to be poor primarily because of the poor pellet quality and heavy dust fouling in combustion chamber and flue gas tubes. R6, R7, R8, R11 and R12 are evaluated to be the best even despite some differences in the parameters.

Emissions

Below the emission results are presented and commented on.
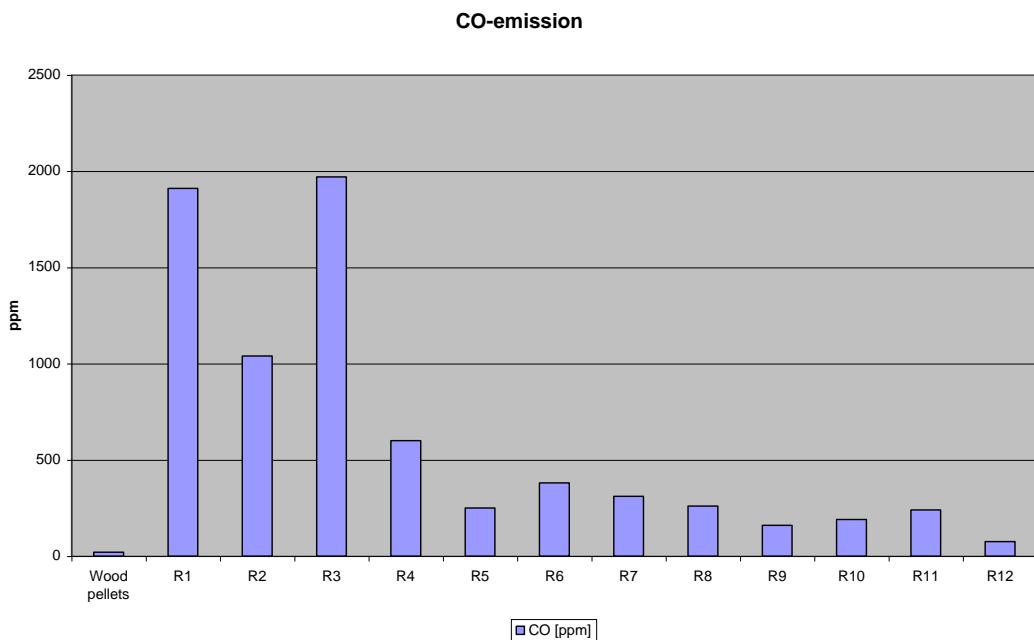
CO-emission

Figure 8-3. The high CO emission in R1, R2 and R3 is caused by slag formation. Until the slag became extensive, the CO emission was low. The CO emission for the other fuels is relatively low and would have been even better if the boiler was adjusted individually for each fuel. The conclusion is that if the pellet quality is high and there is no slag in the ash, the combustion quality is good.
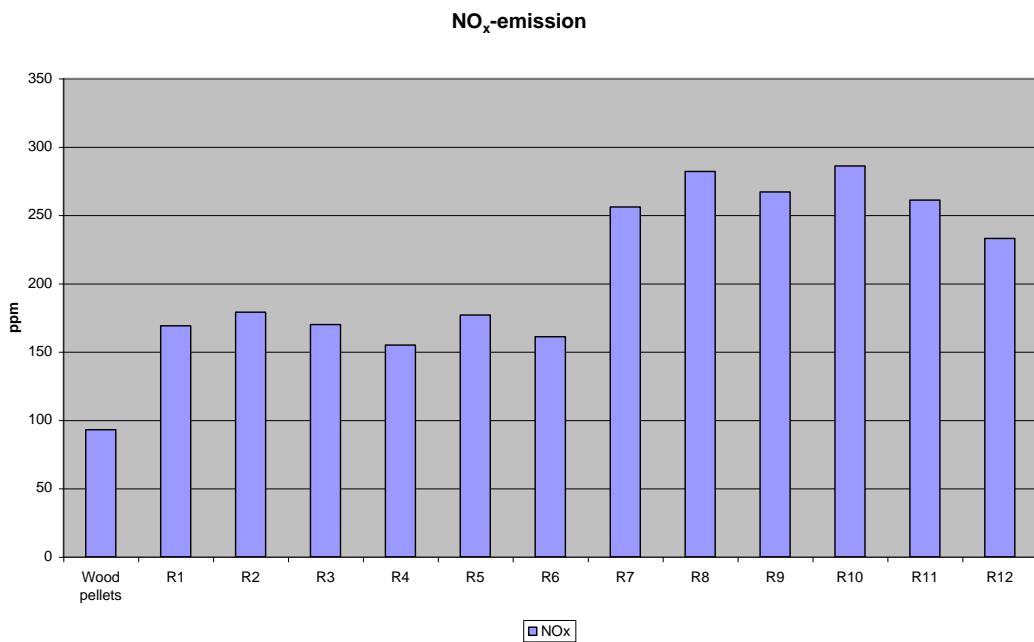
NO$_x$-emission

Figure 8-4. In general, the NO$_x$ emissions for the test fuels are high compared to wood pellets. In R1-R6 the base material is straw, and in R7-R12 the base material is grain screenings. The higher NO$_x$ emission in R7-R12 is due to the fact that grains have a higher nitrogen content than straw.
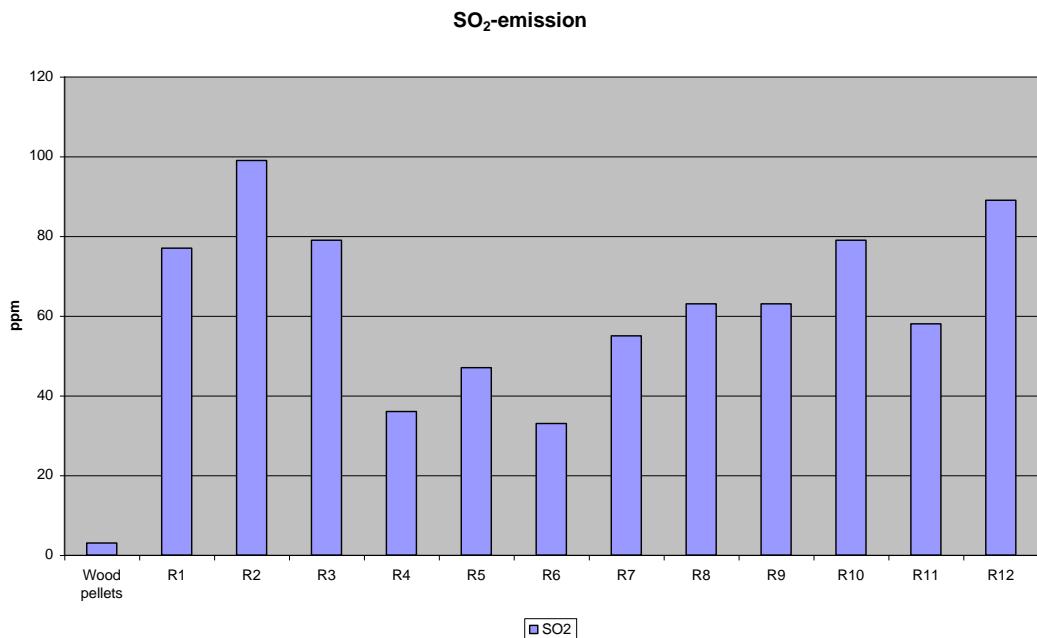
SO$_2$-emission

Figure 8-5. The SO$_2$ emissions for the test fuels are very high compared to wood pellets. The SO$_2$ emission for wood pellets is approximately zero because the sulphur content in wood is very limited.

Dust emission
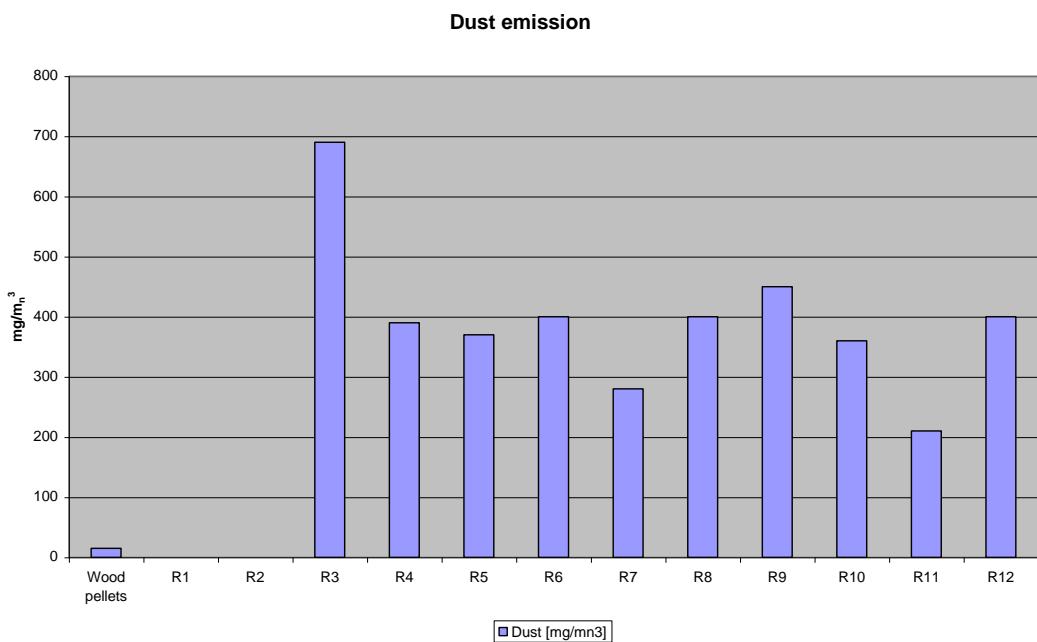
Figure 8-6. The difference between wood pellets and the rest of the fuels is considerable.

Other comparisons

Temperatures in combustion chamber
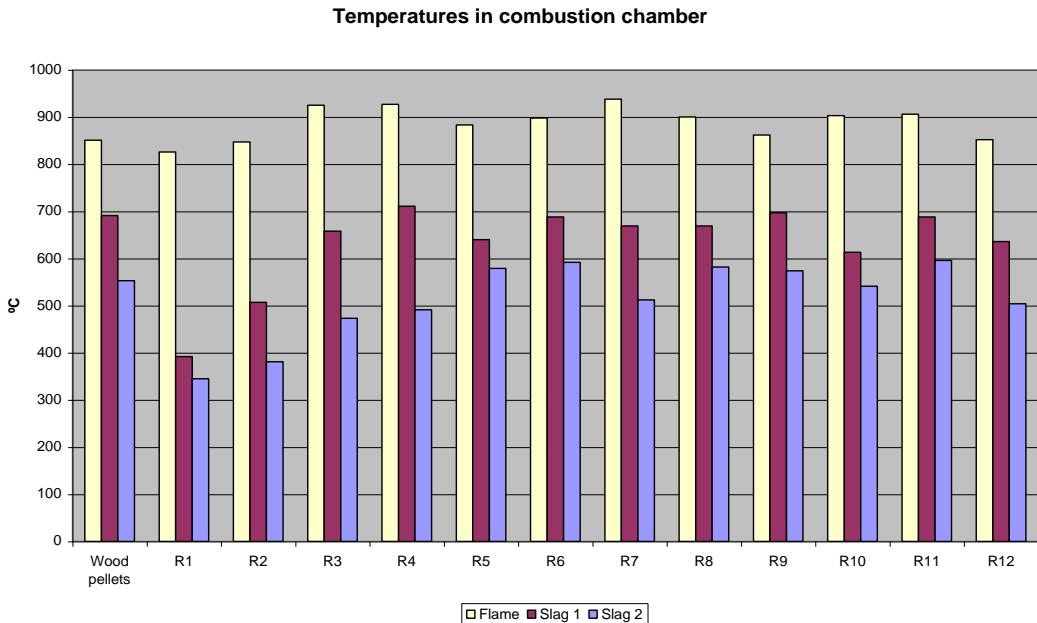
Figure 8-7. The slag temperatures for R1 and R2 is somewhat lower than for the rest of the fuels. This is due to the fact that the slag was very extensive and therefor the combustion was poor. The differences between the rest of the tests are limited.

Unburned in the ash
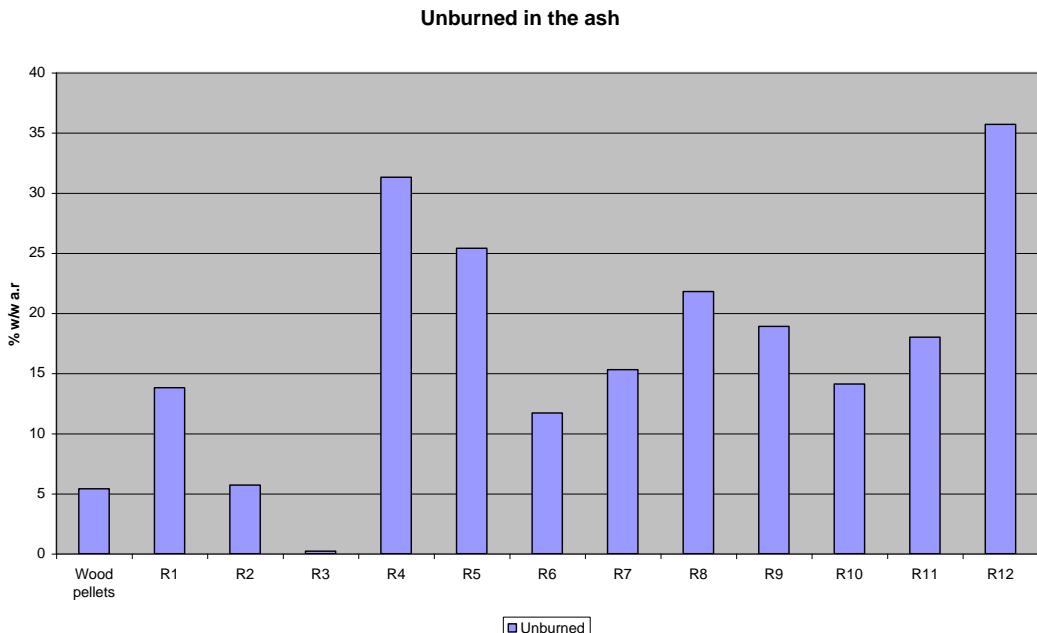
Figure 8-8. The very low figure for R3 is due to heavy slag formation. A large quantity of slag can ensure that the fuel stays in the combustion chamber until it is completely burned out. The high figures for the rests of the fuels have two main reasons: The first reason is that the step grate moves frequently which means that the fuel is pushed into the ash box before it is completely combusted. The second reason is that the primary air supply is limited because of the fixed slag formation at the nozzles.

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8.8. Extracts from the tests

Below examples of the most important parameters are shown.

Slag in the ash

Picture 8-2. Typical slag formation. Slag from R3.

Picture 8-3. Typical slag formation. Slag from R3.

Crumbly ash without slag

Picture 8-4. Typical ash quantity in the boiler when there is no slag. Ash from R4.

Picture 8-5. Typical ash consistency when there is no slag. Ash from R8.

Fixed slag at the air nozzles

Picture 8-6. Clean combustion chamber.

Picture 8-7. Typical picture of fixed slag. The fixed slag is primarily concentrated at the primary air nozzle. From R10.

Dust fouling in flue gas tubes

Picture 8-8. Clean flue gas tubes before the test.

Picture 8-9. The worst case of fouling after 65 hours. From R4.

Pellet quality

Picture 8-10. High pellet quality. R8.

Picture 8-11. Poor pellet quality. R4.

8.9. Test results

Wood pellets - 8 mm pellets .... tested 14.06.01-15.06.01

Fuel Pure sawdust

Test duration 24 hours at nominal heat output. Completed successfully.

Combustion quality In general, the combustion was very good with very low CO and no peaks.

Slag formation No slag.

Dust fouling Combustion chamber and flue gas tubes were very slightly fouled (less than 1 mm). The flue gas temperature increased less than 5 °C.

Evaluation No problems. Constantly very god combustion, steady heat output and steady flue gas temperature. High pellet quality.

Measurement	Unit	Day 1	Day 2	Day 3	Average
Heat output	kW	31.5	-	-	31.5
Fuel consumption	kg/h	-	-	-	7.6
Water content in the fuel	%	-	-	-	8.0
Boiler efficiency	%	-	-	-	88
Flue gas temperature	°C	122	-	-	122
CO_2 measured	%vol	14.3	-	-	14.3
CO at 10% O_2	ppm	20	-	-	20
CO at 10% O_2	mg/m_n^3	25	-	-	25
NO_x (as NO_2) at 10% O_2	ppm	93	-	-	93
NO_x (as NO_2) at 10% O_2	mg/m_n^3	191	-	-	191
SO_2 at 10% O_2	ppm	3	-	-	3
SO_2 at 10% O_2	mg/m_n^3	8	-	-	8
Dust at 10% O_2	mg/m_n^3	15	-	-	15
Flame	°C	851	-	-	851
Slag 1	°C	691	-	-	691
Slag 2	°C	553	-	-	553
Ash formation during the test	kg/h	0.02			
Unburned in the ash	% w/w a.r.	5.4			

Table 8-4. Test results. All emission values are referred to dry flue gas.

**Heat output, CO$_2$, CO and flue gas temperature**
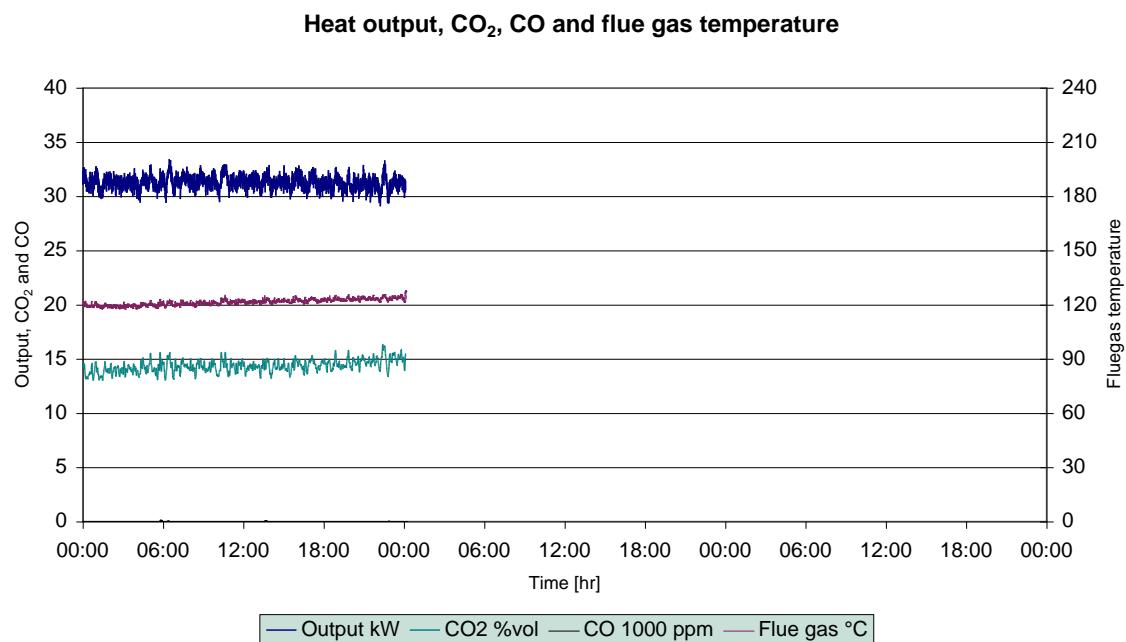
Figure 8-9. The CO emission is very low and there are no peaks. The heat output is steady and the flue gas temperature only increases slightly.
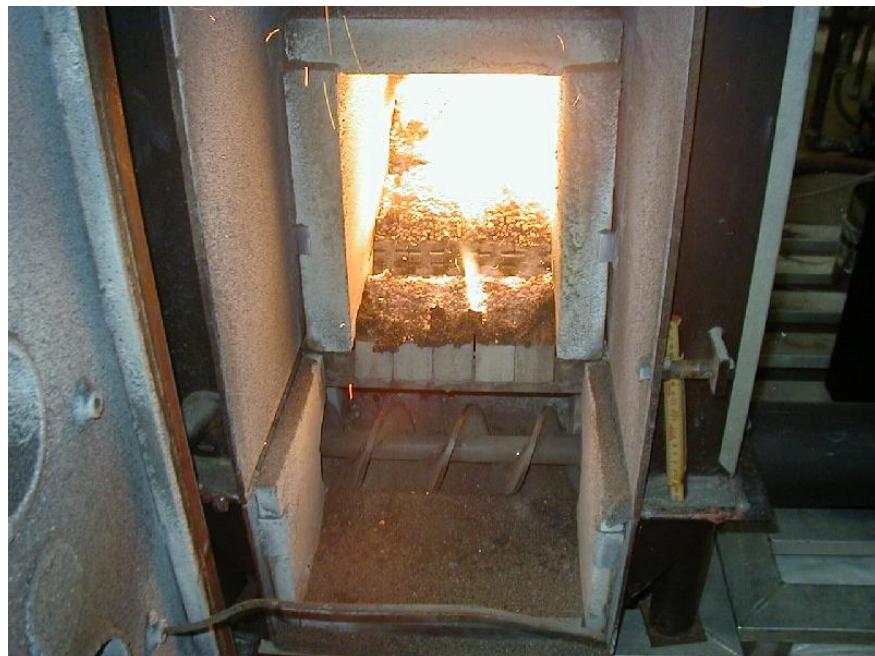
Picture 8-12. The picture was taken shortly before shut down. The combustion chamber was very slightly fouled. Very small quantity of ash in the ash box. No slag was found.

R1 - 12 mm pellets...tested 11.06.01-12.06.01

Fuel   1/1 straw, 1% aluminium hydroxide

Test duration   16 hours at nominal heat output. The test was stopped because of
                            heavy slag formation in the combustion chamber.

Combustion quality   The combustion was very good as long as there was no slag. When
                            the slag became extensive, the combustion became very bad.

Slag formation   Serious slag formation in the combustion chamber. The chamber
                            was almost closed at the end of the test. The test duration was too
                            short to observe if fixed slag would occur.

Dust fouling   Combustion chamber and flue gas tubes were heavily fouled
                            (approx. 2-3 mm).

Evaluation   The heavy slag formation makes the fuel useless. In addition, the
                            fuel emitted at lot of dust when it was filled into the fuel hopper.
                            Combustion chamber and flue gas tubes were heavily fouled.

Measurement	Unit	Day 1	Day 2	Day 3	Average
Heat output	kW	31.7	-	-	31.7
Fuel consumption	kg/h	-	-	-	11.2
Water content in the fuel	%	-	-	-	10.6
Boiler efficiency	%	-	-	-	-
Flue gas temperature	°C	139	-	-	139
CO_2 measured	%vol	11.0	-	-	11.0
CO at 10% O_2	ppm	1884	-	-	1884
CO at 10% O_2	mg/m_n^3	2355	-	-	2355
NO_x (as NO_2) at 10% O_2	ppm	167	-	-	167
NO_x (as NO_2) at 10% O_2	mg/m_n^3	343	-	-	343
SO_2 at 10% O_2	ppm	76	-	-	76
SO_2 at 10% O_2	mg/m_n^3	219	-	-	219
Dust at 10% O_2	mg/m_n^3	-	-	-	-
Flame	°C	826	-	-	826
Slag $_1$	°C	392	-	-	392
Slag $_2$	°C	345	-	-	345
Ash formation during the test	kg/h	-			
Unburned in the ash	% w/w a.r.	13.8			

Table 8-5. Test results. All emission values are referred to dry flue gas.

Heat output, CO₂, CO and flue gas temperature
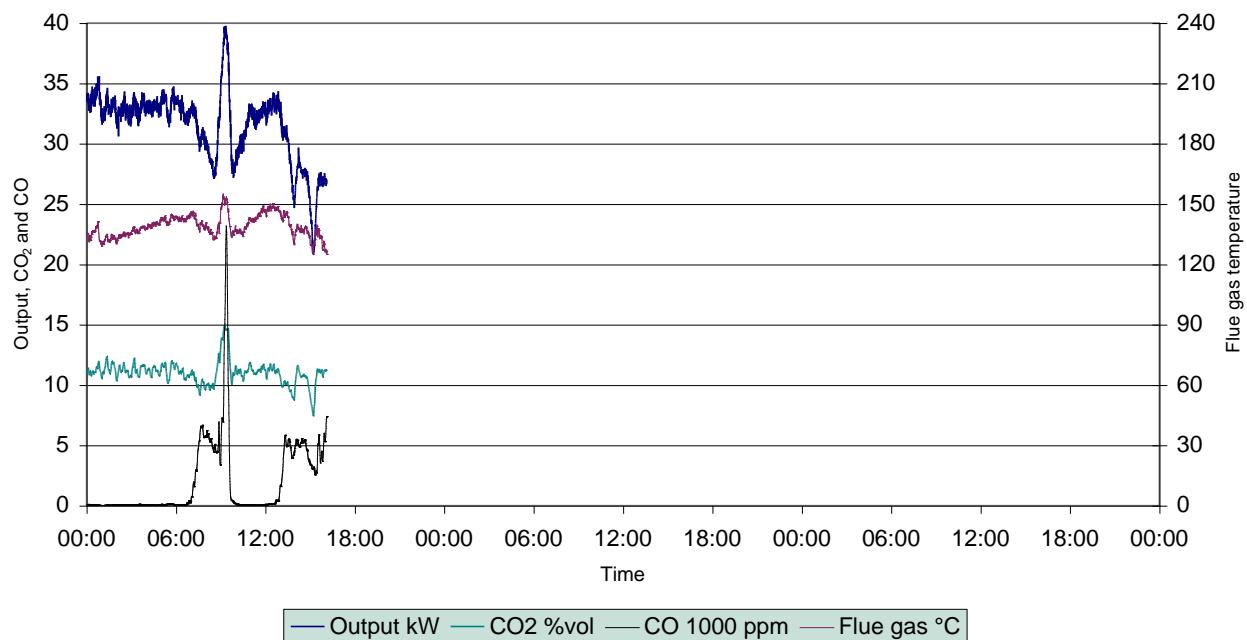
Figure 8-10. The CO emission was very low until the slag had built up. When the slag became extensive, the combustion became very poor and everything became unstable.

Picture 8-13. The picture was taken shortly before shut down. There was a lot of slag which the ash screw had not been able to remove. This made the fuel accumulate in the combustion chamber. When the boiler door was opened, some of the slag fell out and the accumulated fuel was ignited.

R2 - 12 mm pellets..tested 12.06.01-13.06.01

Fuel	1/1 straw, 2% kaolinite
Test duration	18 hours at nominal heat output. The test was stopped because of heavy slag formation in the combustion chamber.
Combustion quality	The combustion was very good as long as there was no slag. When the slag became extensive, the combustion became very poor.
Slag formation	Heavy slag formation in the combustion chamber. The chamber was almost closed at the end of the test. The test duration was too short to observe if fixed slag would occur.
Dust fouling	Combustion chamber and flue gas tubes were heavily fouled (approx. 2-3 mm).
Evaluation	The heavy slag formation makes the fuel useless. In addition, the pellets emitted at lot of dust when they were filled into the fuel hopper. Combustion chamber and flue gas tubes were very heavily fouled.

Measurement	Unit	Day 1	Day 2	Day 3	Average
Heat output	kW	32.5	-	-	32.5
Fuel consumption	kg/h	-	-	-	10.6
Water content in the fuel	%	-	-	-	12.9
Boiler efficiency	%	-	-	-	-
Flue gas temperature	°C	137	-	-	137
CO_2 measured	%vol	10.8	-	-	10.8
CO at 10% O_2	ppm	1021	-	-	1021
CO at 10% O_2	mg/m_n^3	1276	-	-	1276
NO_x (as NO_2) at 10% O_2	ppm	177	-	-	177
NO_x (as NO_2) at 10% O_2	mg/m_n^3	363	-	-	363
SO_2 at 10% O_2	ppm	97	-	-	97
SO_2 at 10% O_2	mg/m_n^3	278	-	-	278
Dust at 10% O_2	mg/m_n^3	-	-	-	-
Flame	°C	847	-	-	847
Slag 1	°C	507	-	-	507
Slag 2	°C	381	-	-	381
Ash formation during the test	kg/h	-			
Unburned in the ash	% w/w a.r.	5.7			

Table 8-6. Test results. All emission values are referred to dry flue gas.

Heat output, CO₂, CO and flue gas temperature
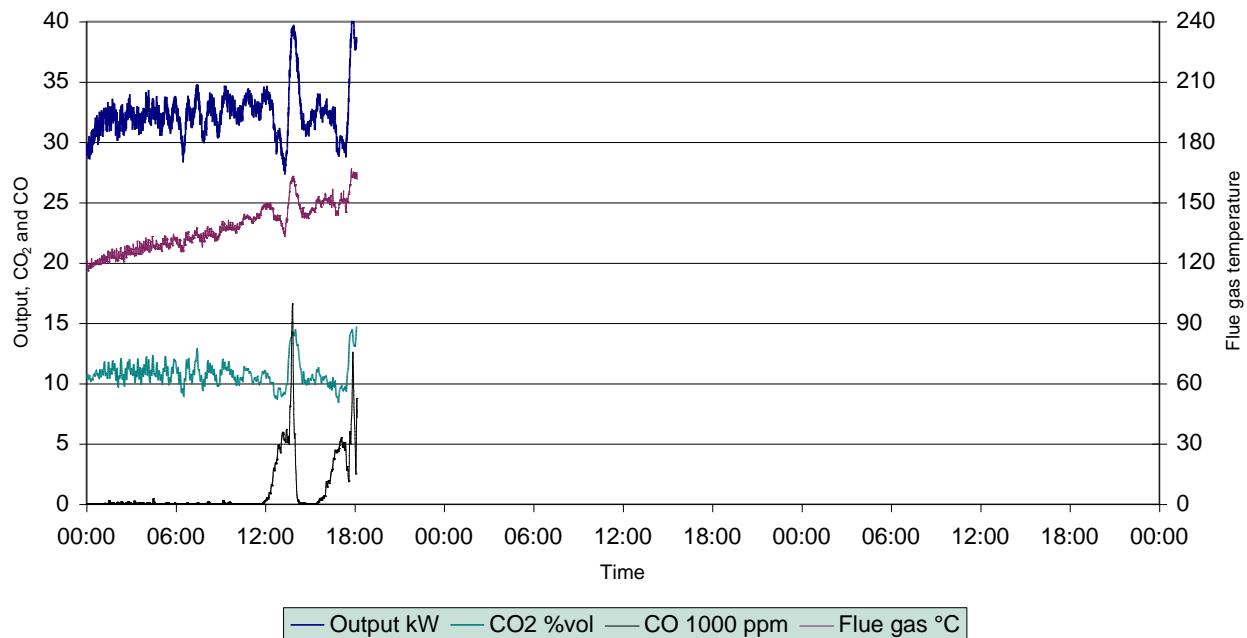
Figure 8-11. The CO emission is very low until the slag has built up. Then it rises dramatically. Note that the flue gas temperature increases rapidly due to the considerable fouling in the flue gas tubes.

Picture 8-14. The picture was taken shortly after shut down. There was a lot of slag which the ash screw had not been able to remove. The combustion chamber was also heavily fouled in spite of the fact that the test duration was very short.

R3 - 12 mm pellets..**tested 17.06.01-19.06.01**

Fuel	1/1 straw, 1% calciumoxide, 3% molasses
Test duration	41 hours at nominal heat output. The test was stopped because of heavy slag formation in the combustion chamber.
Combustion quality	The combustion was very good as long as there was no slag. When the slag became extensive, the combustion became very bad.
Slag formation	Serious slag formation in the combustion chamber. The slag had pushed the refractory in the top of the combustion chamber to the ash box. Serious formations of slag were found at the air nozzles.
Dust fouling	Combustion chamber and flue gas tubes were heavily fouled (approx. 3-4 mm).
Evaluation	The heavy slag formation makes the fuel useless. In addition, the pellets emitted at lot of dust when they were filled into the fuel hopper. Combustion chamber and flue gas tubes were heavily fouled.

Measurement	Unit	Day 1	Day 2	Day 3	Average
Heat output	kW	31.1	28.4	-	30.0
Fuel consumption	kg/h	-	-	-	9.4
Water content in the fuel	%	-	-	-	12.5
Boiler efficiency	%	-	-	-	-
Flue gas temperature	°C	140	164	-	152
CO_2 measured	%vol	13.9	13.0	-	13.5
CO at 10% O_2	ppm	98	3886	-	1933
CO at 10% O_2	mg/m_n^3	123	4858	-	2417
NO_x (as NO_2) at 10% O_2	ppm	181	151	-	167
NO_x (as NO_2) at 10% O_2	mg/m_n^3	372	310	-	342
SO_2 at 10% O_2	ppm	69	86	-	77
SO_2 at 10% O_2	mg/m_n^3	197	247	-	221
Dust at 10% O_2	mg/m_n^3	679	-	-	679
Flame	°C	865	984	-	925
Slag $_1$	°C	780	535	-	658
Slag $_2$	°C	672	273	-	473
Ash formation during the test	kg/h	-			
Unburned in the ash	% w/w a.r.	0.2			

Table 8-7. Test results. All emission values are referred to dry flue gas.

**Heat output, CO₂, CO and flue gas temperature**
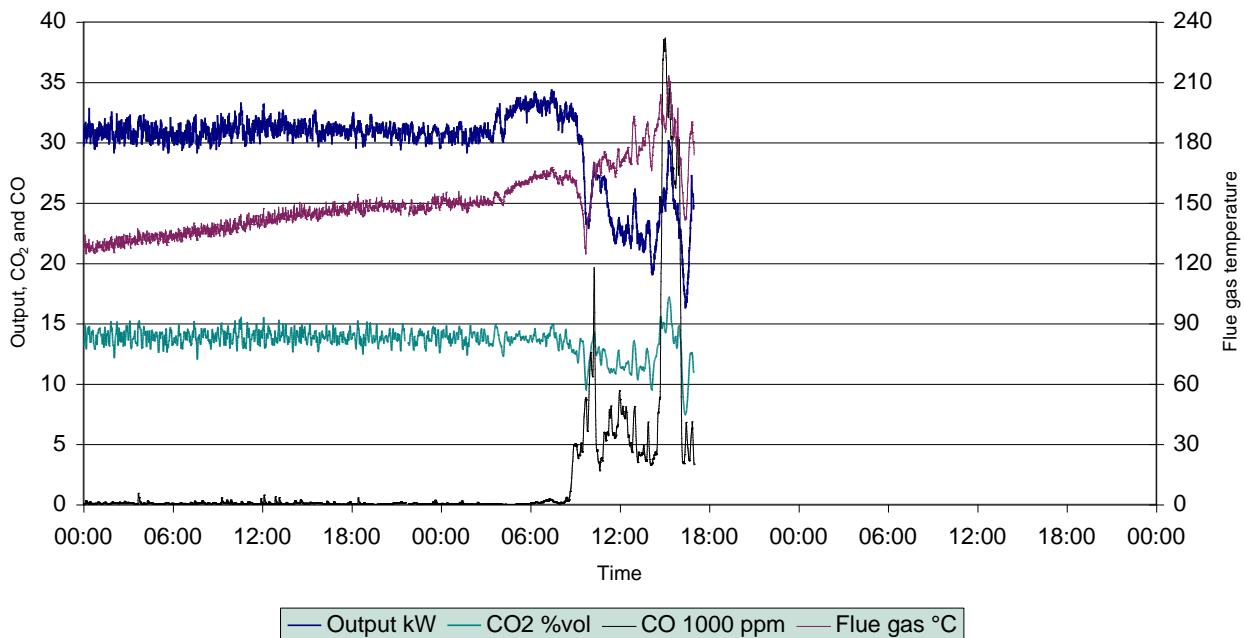
Figure 8-12. The CO emission is very low and the output is stable until the slag becomes extensive. After approx. 7 hours of testing on the second day, the combustion chamber is closed with slag and unburned fuel. 3-4 hours later the slag removes the refractory at the top of the chamber and the boiler starts to perform again, but the combustion is of course very poor and becomes even poorer before the test is stopped.

Picture 8-15. The picture was taken shortly after shut down. The combustion chamber was completely filled with slag. In addition, the combustion chamber was heavily fouled.

R4 - 12 mm pellets..**tested 05.08.01-08.08.01**

Fuel	1/3 sawdust, 2/3 straw, 5% limestone
Test duration	65 hours at nominal heat output. Completed successfully.
Combustion quality	The combustion was very unstable and there were many high CO peaks. In general, CO was medium.
Slag formation	The ash was crumbly and no slag was found. However, serious formations of fixed slag were found at the air nozzles.
Dust fouling	Combustion chamber and flue gas tubes were very heavily fouled (approx. 5-10 mm). The flue gas temperature increased approx. 40 ℃.
Evaluation	The fuel is usable as there is no slag in the ash, but the quality is poor. It creates serious formations of fixed slag at the air nozzles and very heavy fouling in the flue gas tubes. When it is filled into the fuel hopper, the fuel emits a very uncomfortable quantity of dust.

Measurement	Unit	Day 1	Day 2	Day 3	Average
Heat output	kW	30.4	28.4	26.9	28.8
Fuel consumption	kg/h	-	-	-	-
Water content in the fuel	%	-	-	-	7.5
Boiler efficiency	%	-	-	-	-
Flue gas temperature	°C	161	176	180	172
CO_2 measured	%vol	13.7	13.7	13.6	13.7
CO at 10% O_2	ppm	497	718	555	590
CO at 10% O_2	mg/m_n^3	622	898	694	738
NO_x (as NO_2) at 10% O_2	ppm	155	153	152	153
NO_x (as NO_2) at 10% O_2	mg/m_n^3	317	314	311	314
SO_2 at 10% O_2	ppm	35	36	34	35
SO_2 at 10% O_2	mg/m_n^3	101	102	97	100
Dust at 10% O_2	mg/m_n^3	400	373	-	387
Flame	°C	917	940	924	927
Slag 1	°C	721	704	708	711
Slag 2	°C	473	501	499	491
Ash formation during the test	kg/h	-			
Unburned in the ash	% w/w a.r.	31.3			

Table 8-8. Test results. All emission values are referred to dry flue gas.

Heat output, CO₂, CO and flue gas temperature
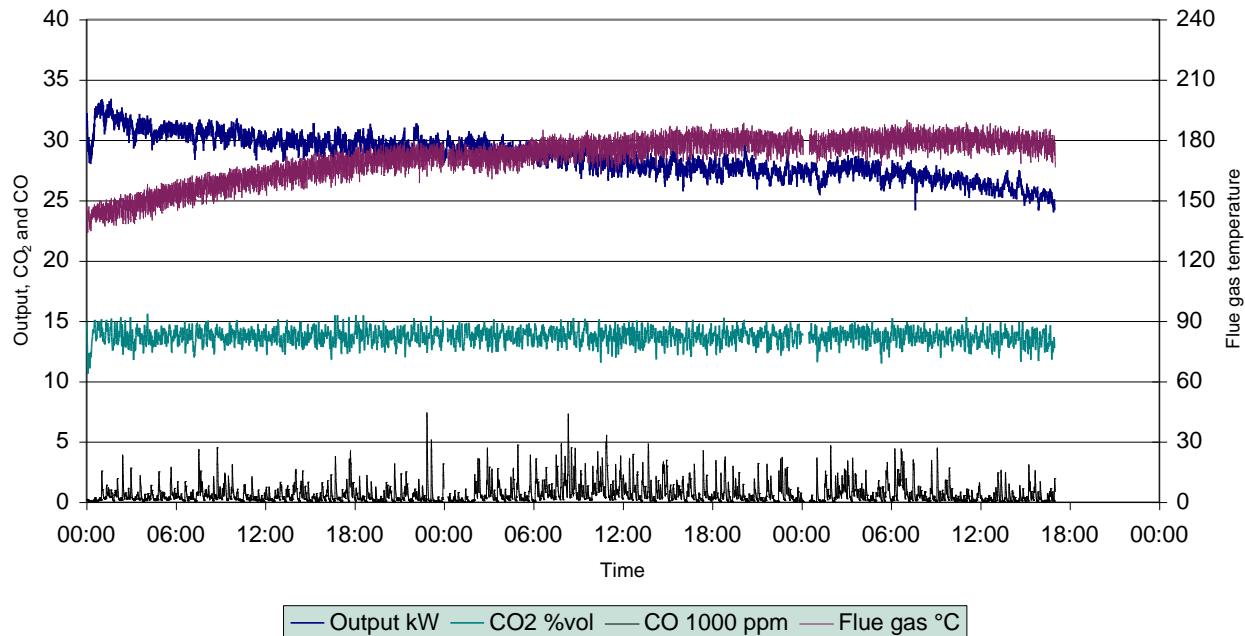
Figure 8-13. In general, the CO emission is medium, but there are many high peaks. Note that the flue gas temperature increases considerably in spite of the fact that the output decreases. This happens due to heavy fouling in the flue gas tubes. The heat output decreases because the air nozzles are covered with fixed slag. This reduces the air supply which makes the PLC controller reduce the fuel supply in order to obtain the requested excess air.

Picture 8-16. The picture was taken shortly after shut down. There was a large quantity of ash in the ash box, but no slag was found because the ash screw had been able to remove the slag continuously. Therefore, the quantity shown in the picture was constant. The combustion chamber was very heavily fouled and fixed slag was found both at the refractory and at the air nozzles.

R5 - 12 mm pellets...tested 08.08.01-10.08.01

Fuel	1/3 sawdust, 2/3 straw, 5% aluminium hydroxide, 5% molasses.
Test duration	45 hours at nominal heat output. Completed successfully. Stopped due to shortage of fuel.
Combustion quality	The combustion was unstable with many high CO peaks. In general, CO was low.
Slag formation	The ash was crumbly with no slag. However, serious formations of fixed slag were found at the air nozzles.
Dust fouling	Combustion chamber and flue gas tubes were very heavily fouled (approx. 3-5 mm). The flue gas temperature increased about 45 °C.
Evaluation	The fuel is usable because no slag is found in the ash, but the quality is poor. It creates a considerable formation of fixed slag at the air nozzles and fouls the flue gas tubes very heavily. When it is filled into the fuel hopper, the fuel emits a considerable quantity of dust.

Measurement	Unit	Day 1	Day 2	Day 3	Average
Heat output	kW	30.6	28.7	-	29.7
Fuel consumption	kg/h	-	-	-	8.9
Water content in the fuel	%	-	-	-	6.5
Boiler efficiency	%	-	-	-	78
Flue gas temperature	°C	152	172	-	162
CO_2 measured	%vol	13.7	13.5	-	13.6
CO at 10% O_2	ppm	312	174	-	243
CO at 10% O_2	mg/m_n^3	390	217	-	304
NO_x (as NO_2) at 10% O_2	ppm	175	172	-	173
NO_x (as NO_2) at 10% O_2	mg/m_n^3	358	353	-	356
SO_2 at 10% O_2	ppm	47	45	-	46
SO_2 at 10% O_2	mg/m_n^3	136	130	-	133
Dust at 10% O_2	mg/m_n^3	367	361	-	364
Flame	°C	873	887	-	879
Slag $_1$	°C	645	635	-	640
Slag $_2$	°C	564	595	-	579
Ash formation during the test	kg/h	0.99			
Unburned in the ash	% w/w a.r.	25.4			

Table 8-9. Test results. All emission values are referred to dry flue gas. Note that the CO emission is somewhat lower on the second day. This is probably due to the fact that the primary air nozzles are covered with slag.

Heat output, CO₂, CO and flue gas temperature
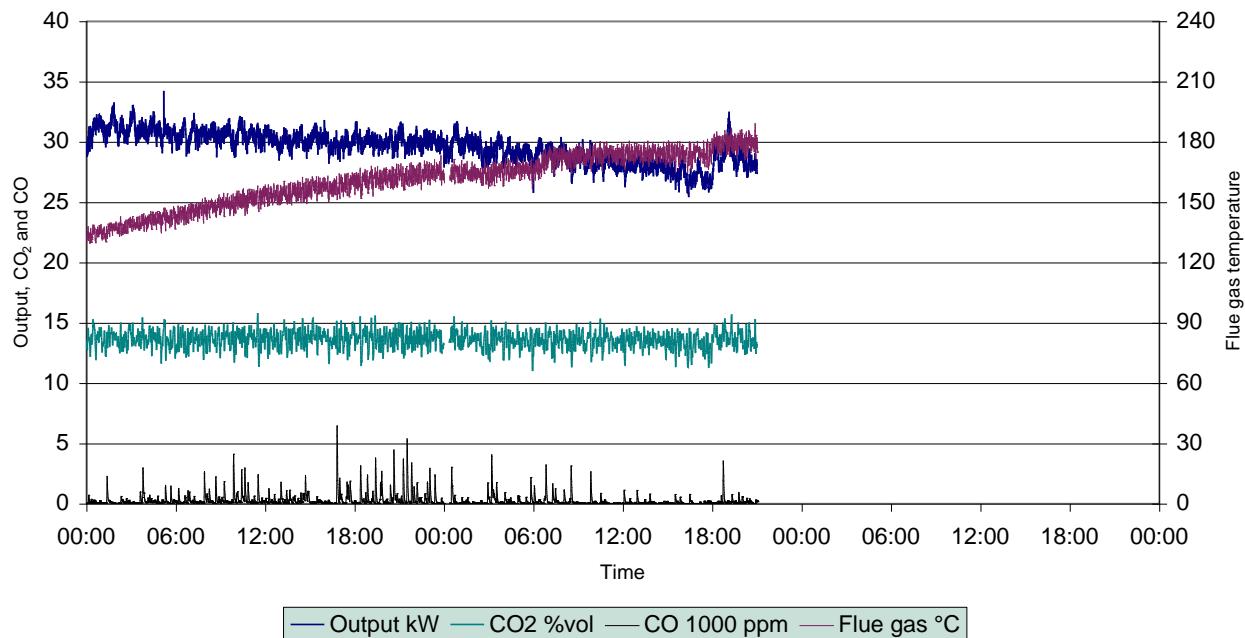
Figure 8-14. In general, the CO emission is low, but some high peaks occur. The flue gas temperature increases a lot because of the heavy fouling in the flue gas tubes. The heat output decreases due to the fact that the air nozzles are covered with slag and therefore the PLC controller reduces the fuel supply.

Picture 8-17. The picture was taken shortly after shut down. There was a large quantity of ash in the ash box, but no slag was found in the ash. The combustion chamber was very heavily fouled and fixed slag was found both at the refractory and at the air nozzles in spite of the fact that the test duration was relatively short.

R6 - 12 mm pellets..tested 09.10.01-12.10.01

Fuel	1/3 sawdust, 2/3 straw, 5% limestone, 5% molasses, 5% rape oil.
Test duration	70 hours at nominal heat output. Completed successfully.
Combustion quality	The combustion was reasonably good with generally low CO, but many high peaks.
Slag formation	No slag in the ash which was easily removed by the ash screw. However, considerable formations of fixed slag were found at the air nozzles.
Dust fouling	Combustion chamber and flue gas tubes were slightly fouled (approx. 2-3 mm). The flue gas temperature increased only approx. 20 °C.
Evaluation	No slag was found in the ash, the fouling was limited and the pellet quality was high. Fixed slag was the only problem. However, this is a serious problem. In order to obtain a good combustion, a high heat output and to avoid unburned fuel in the ash, the fixed slag must be removed from the air nozzles at least every second day.

Measurement	Unit	Day 1	Day 2	Day 3	Average
Heat output	kW	31.6	30.3	28.5	30.2
Fuel consumption	kg/h	-	-	-	8.7
Water content in the fuel	%	-	-	-	11.7
Boiler efficiency	%	-	-	-	81
Flue gas temperature	°C	155	159	159	158
CO_2 measured	%vol	13.7	13.5	13.6	13.6
CO at 10% O_2	ppm	453	407	234	365
CO at 10% O_2	mg/m_n^3	566	509	293	456
NO_x (as NO_2) at 10% O_2	ppm	156	157	150	154
NO_x (as NO_2) at 10% O_2	mg/m_n^3	321	323	307	317
SO_2 at 10% O_2	ppm	30	34	31	32
SO_2 at 10% O_2	mg/m_n^3	86	98	87	90
Dust at 10% O_2	mg/m_n^3	388	-	380	384
Flame	°C	892	902	900	898
Slag $_1$	°C	666	688	709	688
Slag $_2$	°C	616	608	553	592
Ash formation during the test	kg/h	0.65			
Unburned in the ash	% w/w a.r.	11.7			

Table 8-10. Test results. All emission values are referred to dry flue gas. Note that the CO emission declines considerably during the test. This is probably due to the fact that the primary air nozzles are covered with slag.

Heat output, CO$_2$, CO and flue gas temperature
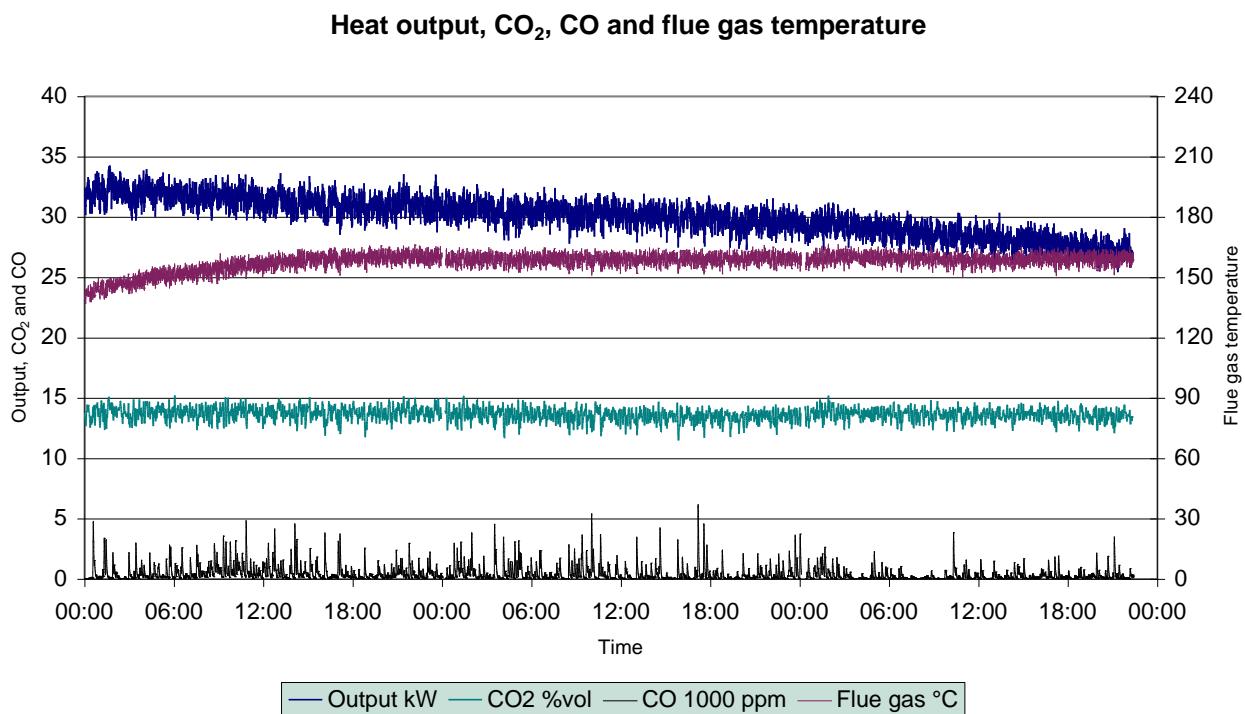
Figure 8-15. In general, the CO emission is low, but there are many high peaks. The flue gas temperature increases slightly due to limited fouling in the flue gas tubes. The heat output decreases because the air nozzles are covered with slag, and therefore the PLC controller reduces the fuel supply.

Picture 8-18. The picture was taken shortly after shut down. There was a large quantity of ash in the ash box, but no slag was found in the ash. The combustion chamber was slightly fouled.

R7 - 12 mm pellets...tested 16.10.01-19.10.01

Fuel   1/3 sawdust, 2/3 grain screenings, 5% limestone, 5% molasses, 3% rape oil.

Test duration   70 hours at nominal heat output. Completed successfully.

Combustion quality   The combustion was good with generally low CO, but with some high peaks.

Slag formation   No slag in the ash which was therefore easily removed by the ash screw. However, considerable formations of fixed slag were found at the air nozzles.

Dust fouling   Combustion chamber and flue gas tubes were slightly fouled (approx. 2-3 mm). The flue gas temperature increased about 25 °C.

Evaluation   No slag was found in the ash. The fouling was limited and the pellet quality was high. The only problem was fixed slag. However, this is a serious problem. In order to obtain a good combustion, a high heat output and to avoid unburned fuel in the ash, the fixed slag must be removed from the air nozzles at least every second day.

Measurement	Unit	Day 1	Day 2	Day 3	Average
Heat output	kW	30.2	28.9	27.4	28.9
Fuel consumption	kg/h	-	-	-	8.4
Water content in the fuel	%	-	-	-	10.6
Boiler efficiency	%	-	-	-	84
Flue gas temperature	°C	138	147	147	144
CO_2 measured	%vol	13.5	13.4	13.4	13.4
CO at 10% O_2	ppm	374	306	191	290
CO at 10% O_2	mg/m_n^3	467	383	238	363
NO_x (as NO_2) at 10% O_2	ppm	244	240	240	241
NO_x (as NO_2) at 10% O_2	mg/m_n^3	499	491	491	494
SO_2 at 10% O_2	ppm	55	51	49	52
SO_2 at 10% O_2	mg/m_n^3	157	146	140	147
Dust at 10% O_2	mg/m_n^3	271	251	260	260
Flame	°C	928	944	943	938
Slag $_1$	°C	654	670	684	669
Slag $_2$	°C	510	513	513	512
Ash formation during the test	kg/h	0.82			
Unburned in the ash	% w/w a.r.	15.3			

Table 8-11. Test results. All emission values are referred to dry flue gas. Note that the CO emission decreases considerably through the test. This is probably due to the fact that the primary air nozzles are covered with slag.

Heat output, CO₂, CO and flue gas temperature
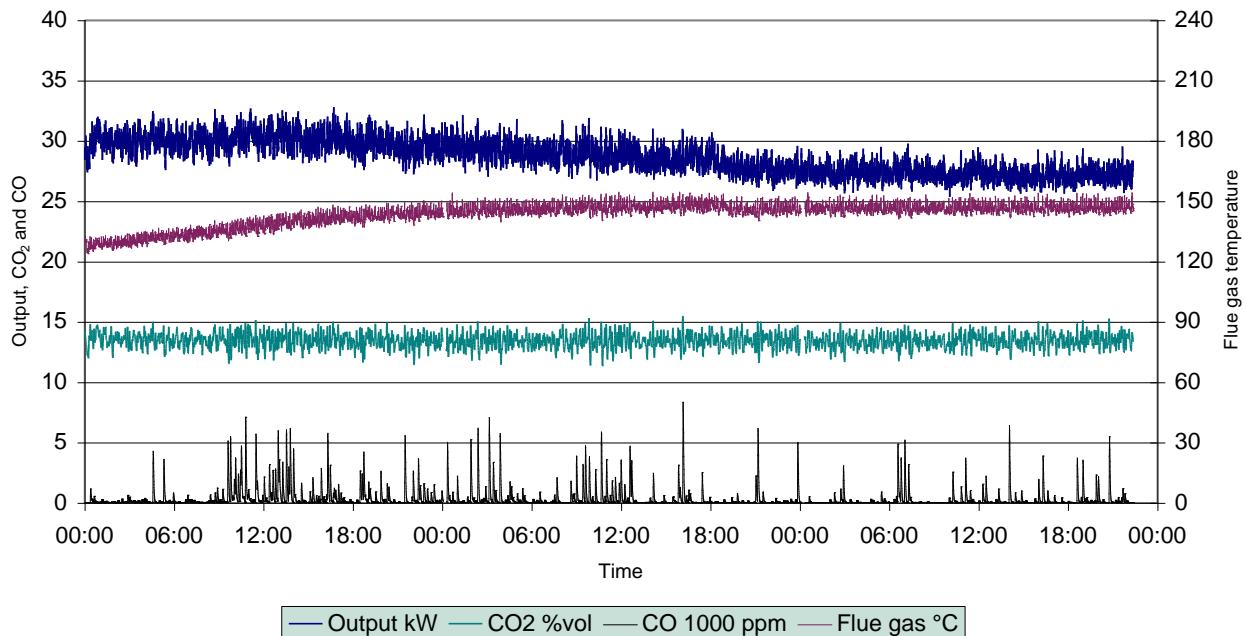
Figure 8-16. In general, the CO emission is low, but there are many high peaks. The peaks probably rise when the step grate moves. The flue gas temperature increases slightly due to limited fouling in the flue gas tubes. The heat output decreases because the air nozzles are covered with fixed slag and therefore the PLC controller reduces the fuel supply.
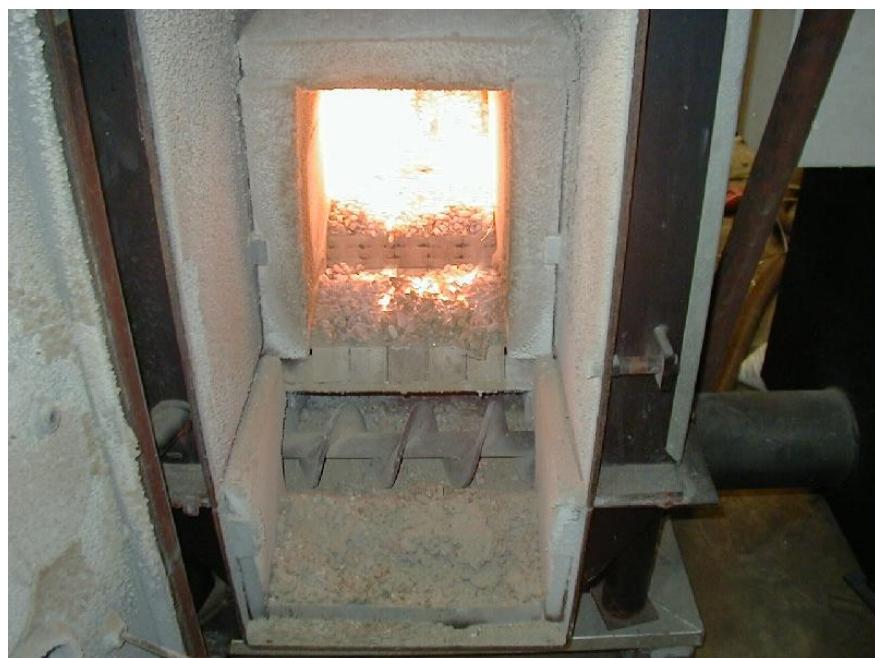
Picture 8-19. The picture was taken shortly before shut down. A large quantity of ash was found in the ash box, but no slag was found. The combustion chamber was slightly fouled.

R8 - 12 mm pellets...tested 13.11.01-16.11.01

Fuel	1/3 sunflower shells, 2/3 grain screenings, 5% limestone, 5% molasses, 2% rape oil.
Test duration	70 hours at nominal heat output. Completed successfully.
Combustion quality	In general, the combustion was good with low CO, but with some high peaks.
Slag formation	No slag was found in the ash and it was therefore easily removed by the ash screw. However, considerable formations of fixed slag were found at the air nozzles.
Dust fouling	Combustion chamber and flue gas tubes were slightly fouled (approx. 2-3 mm). The flue gas temperature increased about 25 °C.
Evaluation	No slag was found in the ash, the fouling was limited and the pellet quality was high. The only problem was fixed slag. However, this is a serious problem. In order to obtain a good combustion, a high heat output and to avoid unburned fuel in the ash, the fixed slag must be removed from the air nozzles at least every second day.

Measurement	Unit	Day 1	Day 2	Day 3	Average
Heat output	kW	29.3	28.8	27.9	28.7
Fuel consumption	kg/h	-	-	-	8.6
Water content in the fuel	%	-	-	-	11.2
Boiler efficiency	%	-	-	-	82
Flue gas temperature	°C	138	150	153	147
CO_2 measured	%vol	13.1	12.9	13.0	13.0
CO at 10% O_2	ppm	267	277	185	243
CO at 10% O_2	mg/m_n^3	334	346	231	304
NO_x (as NO_2) at 10% O_2	ppm	266	264	266	265
NO_x (as NO_2) at 10% O_2	mg/m_n^3	546	541	545	544
SO_2 at 10% O_2	ppm	61	60	57	59
SO_2 at 10% O_2	mg/m_n^3	174	172	163	170
Dust at 10% O_2	mg/m_n^3	374	373	372	373
Flame	°C	895	900	905	900
Slag $_1$	°C	653	668	687	669
Slag $_2$	°C	573	579	594	582
Ash formation during the test	kg/h	0.90			
Unburned in the ash	% w/w a.r.	21.8			

Table 8-12. Test results. All emission values are referred to dry flue gas. Note that the CO emission is somewhat lower the last day. This is probably due to the fact that the primary air nozzles are covered with slag.

**Heat output, CO₂, CO and flue gas temperature**
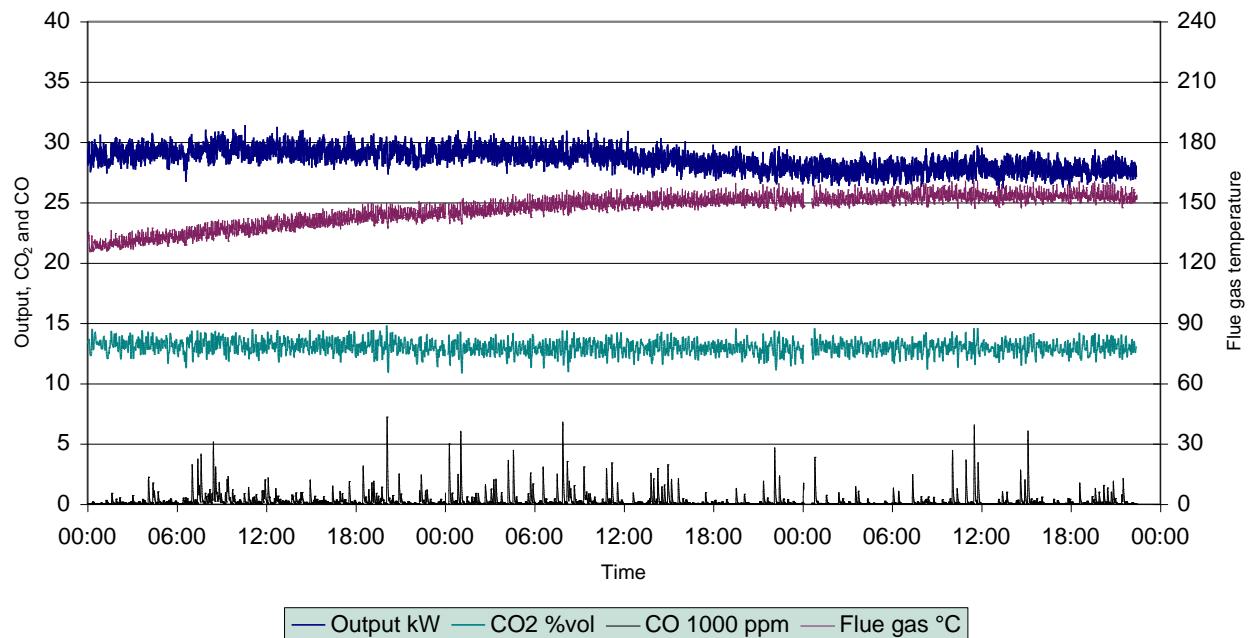
*Figure 8-17. In general, the CO emission is low, but there are many high peaks. The peaks probably rise when the step grate moves. The flue gas temperature increases slightly due to the limited fouling in the flue gas tubes.*
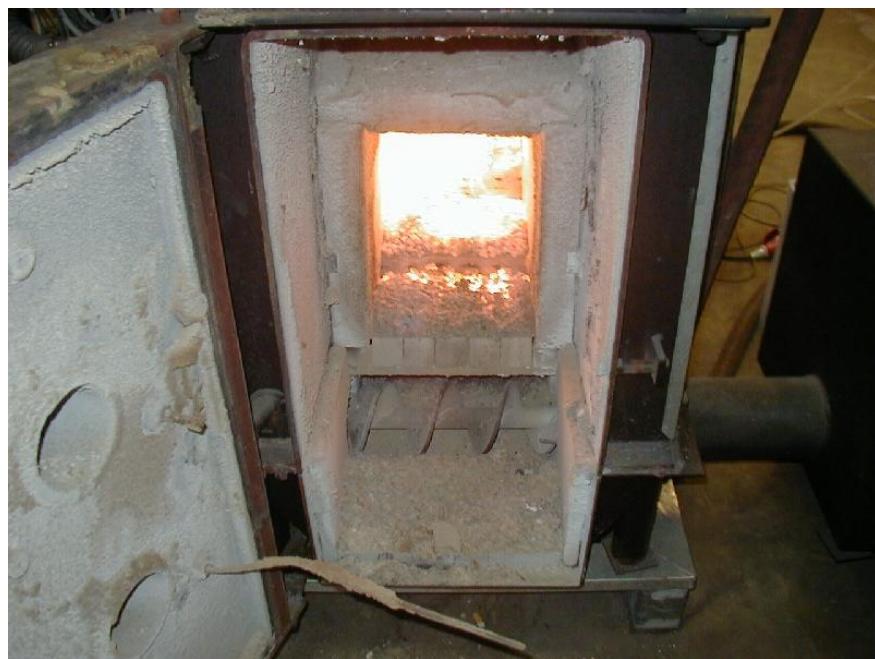
Picture 8-20. The picture was taken shortly before shut down. A large quantity of ash was found in the ash box, but no slag was found. The combustion chamber was slightly fouled.

R9 - 12 mm pellets..tested 19.11.01-22.11.01

Fuel   1/3 shea nut shells, 2/3 grain screenings, 5% limestone, 5% molasses, 2% rape oil

Test duration   70 hours at nominal heat output. Completed successfully.

Combustion quality   In general, the combustion was very good with low CO and only a few high peaks.

Slag formation   A small quantity of slag was found in the ash, but it was crumbly and therefore easily removed by the ash screw. Serious formations of fixed slag were found at the air nozzles.

Dust fouling   Combustion chamber and flue gas tubes were slightly fouled (approx. 2-3 mm). The flue gas temperature increased about 25 °C.

Evaluation   The fouling was limited and the pellet quality was high. There was a small quantity of slag in the ash, but it was crumbly and therefore no problem. The only problem was fixed slag. However, this is a serious problem. In order to obtain a good combustion, a high heat output and to avoid unburned fuel in the ash, fixed slag must be removed from the air nozzles at least every second day.

Measurement	Unit	Day 1	Day 2	Day 3	Average
Heat output	kW	28.5	27.4	26.5	27.5
Fuel consumption	kg/h	-	-	-	8.9
Water content in the fuel	%	-	-	-	14.0
Boiler efficiency	%	-	-	-	82
Flue gas temperature	°C	133	144	148	142
CO_2 measured	%vol	12.6	12.6	13.1	12.8
CO at 10% O_2	ppm	190	146	127	154
CO at 10% O_2	mg/m_n^3	238	182	159	192
NO_x (as NO_2) at 10% O_2	ppm	239	249	269	253
NO_x (as NO_2) at 10% O_2	mg/m_n^3	491	509	551	518
SO_2 at 10% O_2	ppm	58	66	55	59
SO_2 at 10% O_2	mg/m_n^3	167	188	156	170
Dust at 10% O_2	mg/m_n^3	432	408	430	423
Flame	°C	852	861	873	862
Slag 1	°C	692	704	696	697
Slag 2	°C	578	583	562	574
Ash formation during the test	kg/h	1.06			
Unburned in the ash	% w/w a.r.	18.9			

Table 8-13. Test results. All emission values are referred to dry flue gas. Note that the CO emission declines during the test. This is probably due to the fact that the primary air nozzles are covered with slag.

Heat output, CO$_2$, CO and flue gas temperature
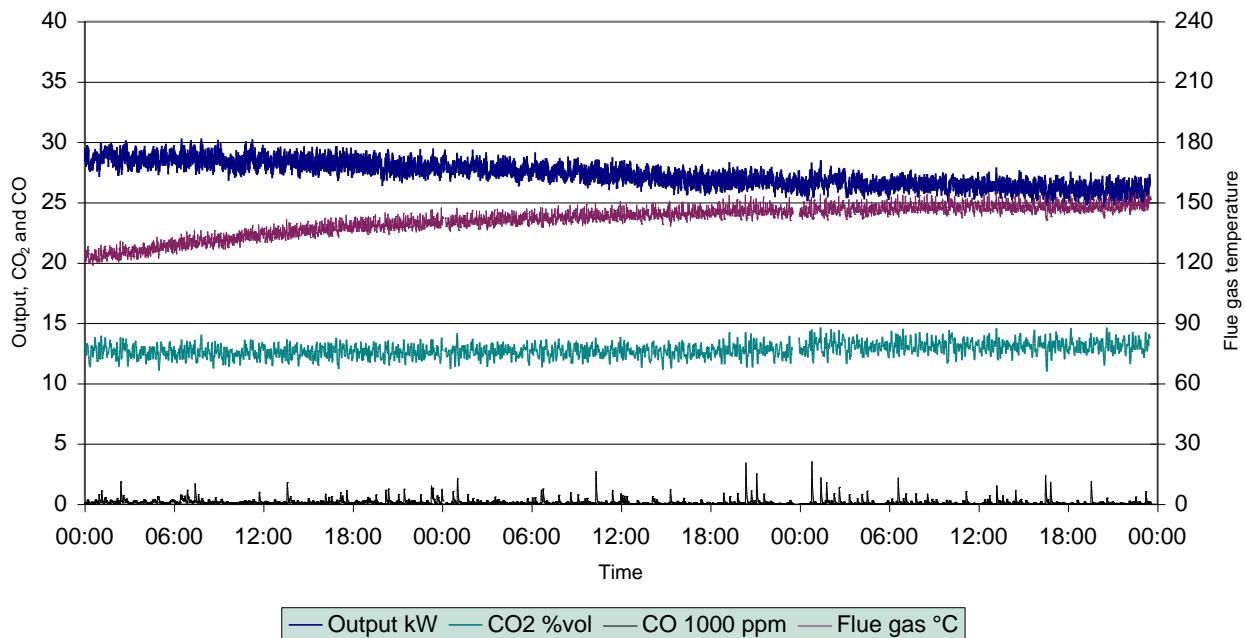
Figure 8-18. In general, the CO emission is low and there are only a few medium high peaks. The flue gas temperature increases slightly. The heat output decreases because the air nozzles are covered with slag.

Picture 8-21. The picture was taken shortly before shut down. There was a small quantity of slag in the ash, but it was crumbly and therefore easily removed by the ash screw. The combustion chamber was slightly fouled.

R10 - 12 mm pellets...tested 03.12.01-06.12.01

Fuel   1/1 grain screenings, 5% limestone, 5% molasses, 2% rape oil.

Test duration   71 hours at nominal heat output. Completed successfully.

Combustion quality In general, the combustion was very good with low CO and only relatively few high peaks.

Slag formation   A small quantity of slag was found in the ash, but it was crumbly and therefore easily removed by the ash screw. Serious formations of fixed slag were found at the air nozzles.

Dust fouling   Combustion chamber and flue gas tubes were slightly fouled (approx. 2-3 mm). The flue gas temperature increased about 30 °C.

Evaluation   The fouling was limited and the pellet quality high. There was a small quantity of slag in the ash, but it was crumbly. The only problem was fixed slag. However, this is a serious problem. In order to obtain a good combustion, a high heat output and to avoid unburned fuel in the ash, the fixed slag must be removed from the air nozzles at least every second day.

Measurement	Unit	Day 1	Day 2	Day 3	Average
Heat output	kW	28.6	27.6	26.9	27.7
Fuel consumption	kg/h	-	-	-	8.8
Water content in the fuel	%	-	-	-	13.1
Boiler efficiency	%	-	-	-	85
Flue gas temperature	°C	132	145	150	142
CO_2 measured	%vol	12.9	12.9	13.4	13.1
CO at 10% O_2	ppm	227	193	120	179
CO at 10% O_2	mg/m_n^3	284	241	150	224
NO_x (as NO_2) at 10% O_2	ppm	262	275	266	268
NO_x (as NO_2) at 10% O_2	mg/m_n^3	537	563	545	548
SO_2 at 10% O_2	ppm	77	75	68	73
SO_2 at 10% O_2	mg/m_n^3	220	215	196	210
Dust at 10% O_2	mg/m_n^3	355	325	335	338
Flame	°C	882	904	924	903
Slag $_1$	°C	616	618	604	613
Slag $_2$	°C	583	534	507	541
Ash formation during the test	kg/h	1.05			
Unburned in the ash	% w/w a.r.	14.1			

Table 8-14. Test results. All emission values are referred to dry flue gas. Note that the CO emission declines during the test. This is probably due the fact that the primary air nozzles are covered with slag.

Heat output, CO$_2$, CO and flue gas temperature
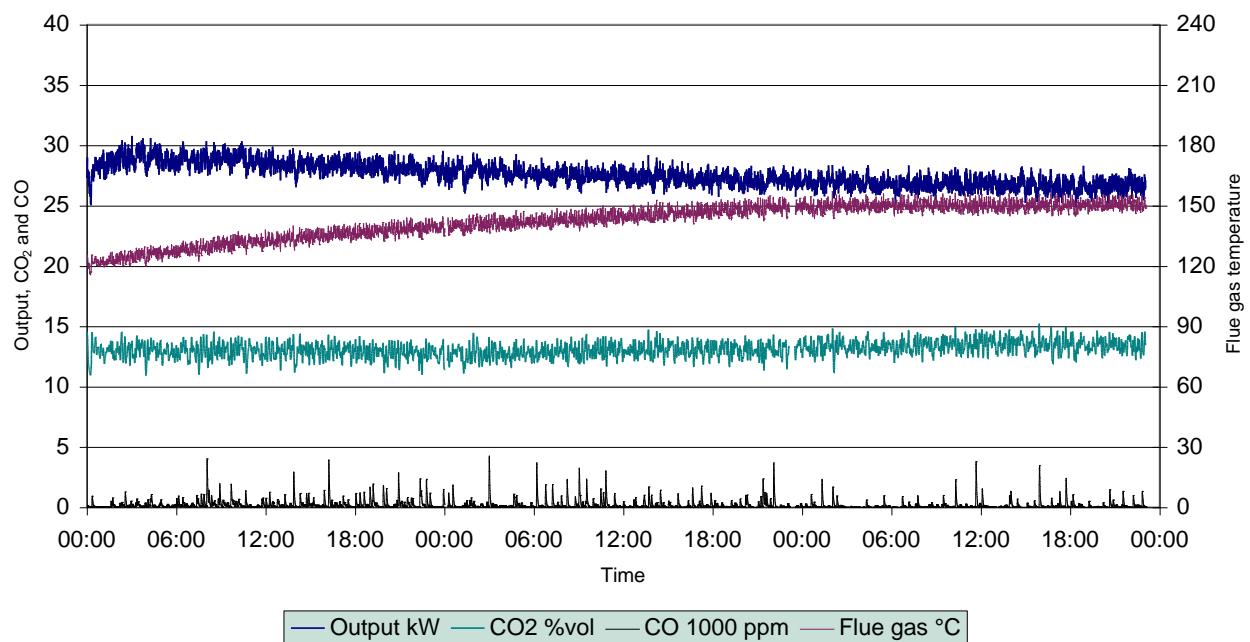
*Figure 8-19. In general, the CO emission is low and there are only a few high peaks. The flue gas temperature increases slightly. The heat output decreases because the air nozzles are covered with slag*

Picture 8-22. The picture was taken shortly before shut down. A small quantity of slag was found in the ash, but it was crumbly and therefore easily removed by the ash screw. The combustion chamber was slightly fouled.

R11 - 12 mm pellets...**tested 21.01.02-24.01.02**

Fuel   1/3 sawdust, 2/3 grain screenings, 3% limestone, 2% molasses, 2% rape oil.

Test duration   71 hours at nominal heat output. Completed successfully.

Combustion quality In general, the combustion was good with low CO, but some high peaks occurred.

Slag formation   No slag was found in the ash. However, considerable formations of fixed slag were found at the air nozzles.

Dust fouling   Combustion chamber and flue gas tubes were very slightly fouled (approx. 2-3 mm). The flue gas temperature only increased approx. 15 ºC.

Evaluation   No slag was found in the ash, the fouling was limited and the pellet quality was high. The only problem was fixed slag. However, this is a serious problem. In order to obtain a good combustion, a high heat output and to avoid unburned fuel in the ash, the fixed slag must be removed from the air nozzles at least every second day.

Measurement	Unit	Day 1	Day 2	Day 3	Average
Heat output	kW	29.0	28.0	27.2	28.1
Fuel consumption	kg/h	-	-	-	8.6
Water content in the fuel	%	-	-	-	12.0
Boiler efficiency	%	-	-	-	80
Flue gas temperature	°C	138	147	149	145
CO_2 measured	%vol	13.3	13.2	13.3	13.2
CO at 10% O_2	ppm	218	275	183	225
CO at 10% O_2	mg/m_n^3	273	344	228	282
NO_x (as NO_2) at 10% O_2	ppm	239	249	257	248
NO_x (as NO_2) at 10% O_2	mg/m_n^3	490	510	526	509
SO_2 at 10% O_2	ppm	54	59	55	56
SO_2 at 10% O_2	mg/m_n^3	153	167	156	159
Dust at 10% O_2	mg/m_n^3	213	199	186	199
Flame	°C	913	906	899	906
Slag $_1$	°C	701	691	674	688
Slag $_2$	°C	594	596	597	596
Ash formation during the test	kg/h	0.92			
Unburned in the ash	% w/w a.r.	18.0			

Table 8-15. Test results. All emission values are referred to dry flue gas.

Heat output, CO₂, CO and flue gas temperature
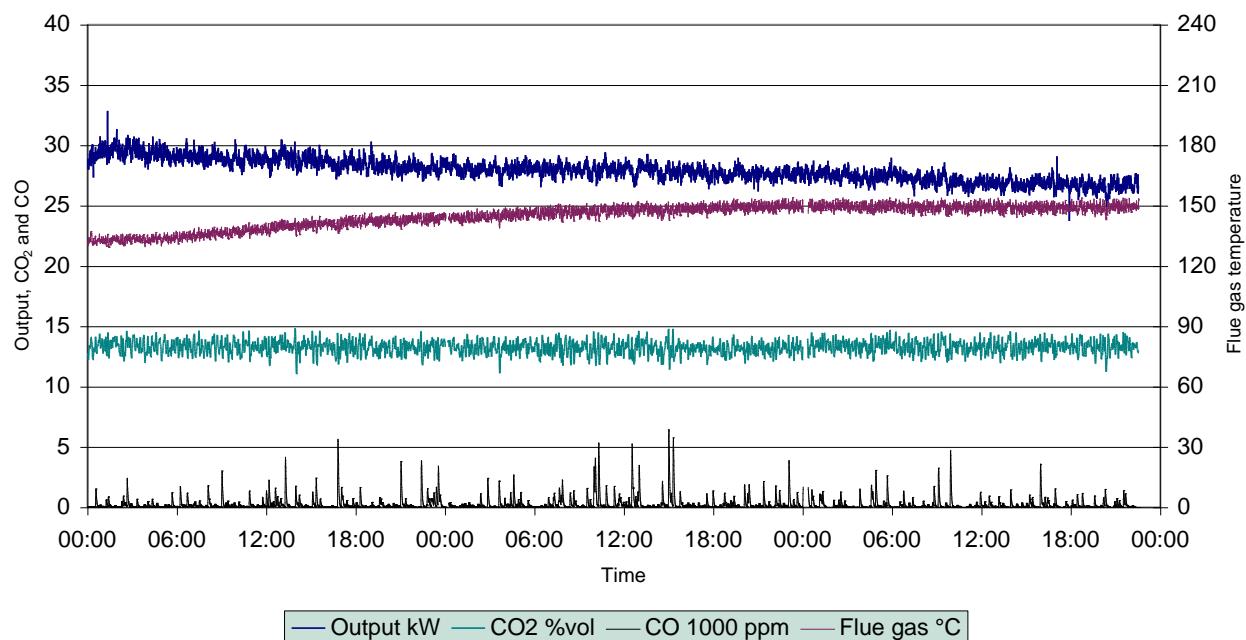
*Figure 8-20. In general, the CO emission is low, but there are some high and many medium high peaks. The flue gas temperature increases very slightly. The heat output decreases because the air nozzles are covered with slag.*
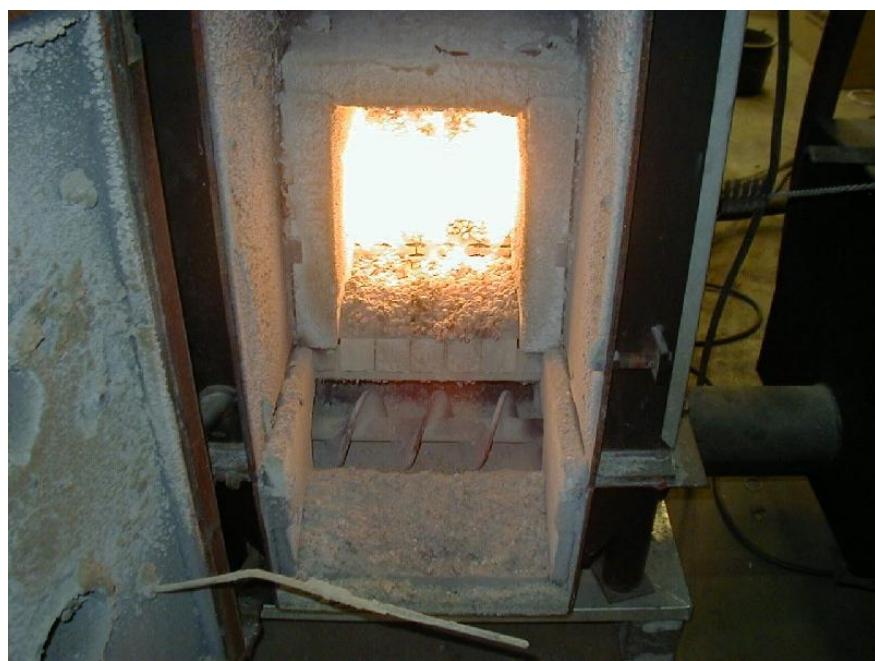
Picture 8-23. The picture was taken shortly before shut down. A large quantity of ash was found in the ash box, but no slag was found in the ash. The combustion chamber was slightly fouled.

R12 - 12 mm pellets..**tested 28.01.02-31.01.02**

Fuel   1/3 shea nut shells, 2/3 grain screenings, 3% limestone.

Test duration   66 hours at nominal heat output. Completed successfully.

Combustion quality   In general, the combustion was very good with very low CO and no peaks.

Slag formation   A small quantity of slag was found in the ash, but it was crumbly and therefore easily removed by the ash screw. Considerable formations of fixed slag were found at the air nozzles.

Dust fouling   Combustion chamber and flue gas tubes were very slightly fouled (approx. 2-3 mm). The flue gas temperature only increased approx. 15 ºC.

Evaluation   The fouling was very limited and the pellet quality was high. There was a small quantity of slag in the ash, but it was crumbly. The only problem was fixed slag. However, this is a serious problem. In order to obtain a good combustion, a high heat output and to avoid unburned fuel in the ash, the fixed slag must be removed from the air nozzles at least every second day.

Measurement	Unit	Day 1	Day 2	Day 3	Average
Heat output	kW	27.6	27.1	26.1	27.0
Fuel consumption	kg/h	-	-	-	9.7
Water content in the fuel	%	-	-	-	14.8
Boiler efficiency	%	-	-	-	74
Flue gas temperature	°C	135	143	142	140
CO_2 measured	%vol	13.2	13.1	13.3	13.2
CO at 10% O_2	ppm	99	64	52	71
CO at 10% O_2	mg/m_n^3	124	79	65	89
NO_x (as NO_2) at 10% O_2	ppm	231	220	215	222
NO_x (as NO_2) at 10% O_2	mg/m_n^3	473	452	440	455
SO_2 at 10% O_2	ppm	89	85	81	85
SO_2 at 10% O_2	mg/m_n^3	255	244	231	243
Dust at 10% O_2	mg/m_n^3	354	421	362	379
Flame	°C	851	846	858	852
Slag $_1$	°C	646	639	623	636
Slag $_2$	°C	490	509	512	504
Ash formation during the test	kg/h	1.34			
Unburned in the ash	% w/w a.r.	35.7			

Table 8-16. Test results. All emission values are referred to dry flue gas. Note that the CO-emission declines considerably during the test. This is probably du to the fact that the primary air nozzles are covered with slag.

Heat output, CO$_2$, CO and flue gas temperature
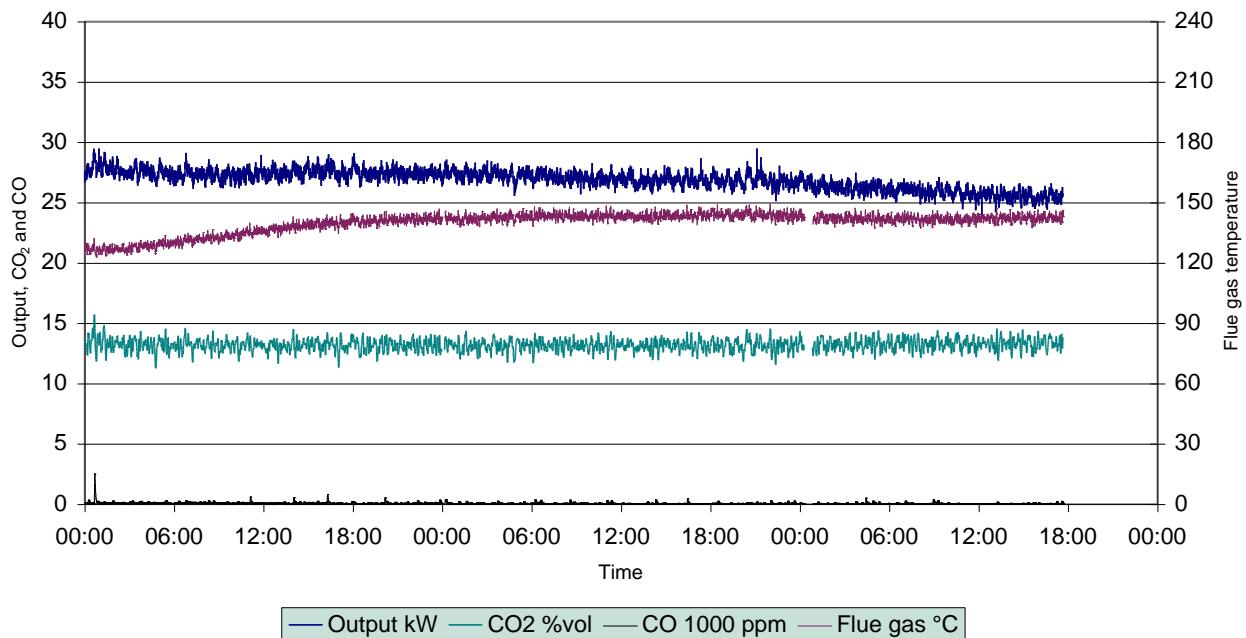
Figure 8-21. In general, the CO emission is very low and there are no peaks. The flue gas temperature only increases slightly. The heat output decreases because the air nozzles are covered with slag.

Picture 8-24. The picture was taken shortly before shut down. A small quantity of slag was found in the ash, but it was crumbly and therefore easily removed by the ash screw. The combustion chamber was very slightly fouled.

8.10. Methods of measurement and measuring equipment

Methods of measurement

- Water content in the fuel was determined according to the weigh/dry method.
- Dust content in the flue gas was determined according to VDI 2066.
- CO and CO_2 were measured with an IR gas analyser.
- NO_x and SO_2 were measured with a NO_2/NO converter and a NDUV gas analyser.
- Flame temperature and slag temperature were measured with a thermocouple type K.
- Water temperature was measured with a Pt-100 sensor.
- Water flow was measured with a magnetic/inductive flow meter.
- Flue gas and room temperature were measured with a thermocouple type K.
- Flue gas draught was measured with an electronic pressure transducer.
- Fuel consumption was determined by weighing.
- Efficiency was determined by the direct method.
- Flue gas was sampled with a heated filter and a sampling hose.
- Measurement equipment was calibrated with zero gas (nitrogen) and span gas during starting-up and after 48 hours.

Measuring equipment

- CO/CO_2 meter, Hartmann & Braun, Uras 14
- NO/SO_2 meter, Hartmann & Braun, Radas 2
- NO_2/NO converter, Hartmann & Braun, CGO-K
- Datalogger, Hewlet Packard, 34970A
- Pt-100 sensor (water temperature)
- Thermocouples, type K (flue gas, ambient temp., slag and flame temperature)
- Pressure gauge, Auto Tran, 700
- Calibrator, Jofra, 650 SE
- Analysis scales, Mettler, PC 440
- Scales, Mettler, PJ 6
- Scales, Sauter, E/9, 60 kg

- Gas meter, IGA AC-5M
- Water flow meter, Danfoss, MAG 1100
- Dust measuring equipment, Ströhlein
- Heated flue gas sampling probe, M & C
- Heated sampling hose, Winkler

9.   Fuel and Ash Analysis

By Klaus Hjuler, dk-TEKNIK ENERGI & MILJØ

9.1.   Analysis work

All raw materials were analysed in detail and the compositions of produced pellets were calculated from the recipes. The advantage of this method was that suggested recipes could be evaluated before the eventual production, and that the analysis costs were reduced. A spreadsheet workbook was elaborated for the calculations, including calculation of various indices to evaluate the suggested recipes.

The raw materials selected for pellet production were analysed using standard methods for upper heating value (ISO 1928), moisture, ash (ISO 1171 modified to 550 °C), and C, H, N (ISO/CD 12902). Oxygen was calculated by difference. The lower heating value was calculated from the content of moisture, S and H.

Laboratory ashes of raw materials were prepared at 550 °C and the ash samples were analysed using scanning electron microscopy with electron dispersive analysis (SEM-EDA) for detection of main inorganic elements. The uncertainty of SEM-EDA is relatively high (compared to traditional digestion and FAAS/ICP), but was considered as being acceptable in this study, because the main purpose of the analyses is to <u>relate</u> the pellet mixtures to each other. The SEM-EDA results were corrected using the so-called PROZA system, which normally should give better results than ZAF concerning low weight elements, and reported on an oxide basis. Using SEM-EDA the weight of the oxides analysed implicitly sums to 100% even though e.g. carbonate that may be a major constituent in some ashes are not detected. S and Cl are exclusively considered as part of the ash although it is known that, say 30-50% of S and Cl are evaporated during ashing. The "missing" mass is replaced by oxygen (by difference). However, this is found to be of minor importance to the results from this study. The analysis reports are found in Appendix 2 as well as the results of standard S (ASTM D3177B) and Cl (PVA 411.2) analyses for comparison.

Molasses and rapeseed oil was used as binding and lubricating agent, respectively, in some pellet recipes. The ash content and composition of molasses were estimated from literature references. Due to the fact that rapeseed oil is essentially free of inorganic constituents, it was not analysed. A literature reference is cited regarding C, H, O, N and heating values. Moreover, 4 additives have been tested, i.e. industrial qualities of CaO, kaolin, $CaCO_3$ and $Al(OH)_3$. Analysis reports from the delivers were used if available, and otherwise the content of impurities was considered to be insignificant to the results of this study.
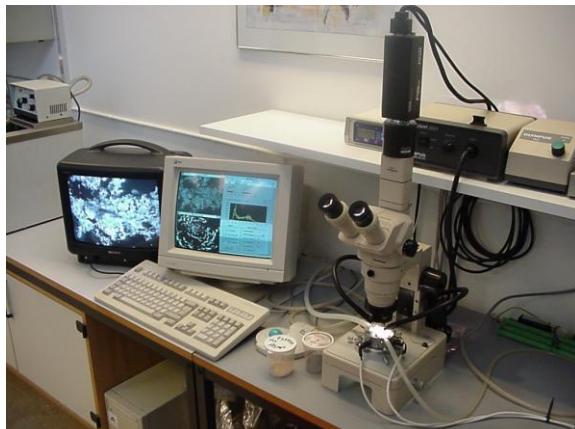
Picture 9-1. Equipment for the MAF Method. A few micrograms of a sample of homogenized (laboratory prepared) ash is placed on a sapphire disc (7 mm in diameter), which is inserted in a gas tight heating stage below a microscope. Nitrogen is used as atmosphere. The microscope is focused on a random part of the sample and the magnification is set at about 100 X.

2-3 kg samples of each of the 12 mixtures produced were milled and ashed in the laboratory at 550 °C. The melting behaviour of the ashes was studied using the "MAF" method (melt area fraction), developed at dk-TEKNIK (Hjuler, K. "Ash Fusibility Detection Using Image Analysis". In "Impact of Mineral Impurities in Solid Fuel Combustion", eds. R. Gupta, T. Wall and L. Baxter. Plenum 1999). In short, this method is based on the behaviour of the ash sample during heating as observed with a microscope using transmitted light.

The sample is heated by 100 °C/min. to 550 °C and after that by 10 °C/min. to approx. 1150 °C. At 550 °C a first image is acquired from which an initial area of the sample is calculated, called A_0, using image analysis. From 550 °C to the final temperature, images are automatically acquired each 5 second and the actual area of the solid part of the sample, called A, is calculated. The analysis result is achieved by plotting $(1-A/A_0)$ x 100% versus the temperature.

The heating stage used for the determination is closed upwards by a glass cover. This cover has a lower temperature than the sample, and consequently volatile components from the sample may condense on its surface. Tests have shown that this only affects the analysis result in extreme cases. An observation of eventual condensation is noticed in the analysis report.

Ash fusion determination by image analysis as described above was developed by dk-TEKNIK especially for ashes from biofuels, where sintering and melting at relatively low temperatures have particular importance.

Ashes sampled from the grate/furnace of the 30 kW boiler (Chapter 8) after each combustion test were milled and analysed for loss of unburned in the ash (ISO 1171 modified to 550 °C).

9.2. Results

The analysis results are summarised in Table 9-1. The fuel analysis is reported as weight percent on an as received basis, whereas the ash analysis is reported as weight percent dry matter.

It can be noticed that the ash content of the raw materials varies from 0.3 to 13% and the moisture content from 9.8 to 16%. Sawdust has by far the lowest and grain screenings the highest ash content. Grain screenings and shea nut shells have relatively high nitrogen contents, even on a water and ash free basis.

It is also noticed that the contents of most ash elements varies significantly (dry basis). The contents of the main potentially glass-forming elements (in this study), i.e. SiO_2, CaO, and K_2O, vary in the range 1-52%, 6-33% and 15-53%, respectively. Sawdust ash has the highest content of CaO, typical of wood ash, which is normally found as limestone. Therefore, the analysis was corrected by adding the stoichiometrical quantity of CO_2.

	Material											
Ash analysis (% w/w ash d.m.)	M1 Wheat straw	M2 Wood	M3 Grain screen	M4 Sunflower	M5 Sheanut	M6 Molasses	M7 Rape seed oil	A1 H2O	A2 CaO	A4 Kaolin	A5 CaCO3	A6 Al(OH)3
SiO2	52,0	4,7	34,4	1,1	6,6					45,7		0,0
Al2O3	0,6	2,1	2,2	0,5	1,7					34,8		60,5
Fe2O3	1,1	0,7	2,6	0,9	2,4					0,0		0,0
CaO	9,2	33,4	15,8	16,0	6,4	3,6			100	0,1	56,0	0,0
MgO	1,8	7,2	3,9	13,1	7,9					0,2		
Na2O	0,3	2,4	1,9	0,0	0,4	20,7				0,1		0,2
K2O	21,9	15,2	19,2	45,1	53,3	57,1				1,3		
SO3	4,0	2,1	5,1	11,7	10,4	12,8	100			0,0		
P2O5	3,2	1,9	11,6	10,1	9,3	0,6				0,1		0,0
CO2, H2O from OH	0,0	26,2	0,0	0,0	0,0					13,1	44,0	39,3
Cl	5,6	0,1	2,8	1,2	1,4	5,1				0,1		
Other	0,3	3,9	0,5	0,3	0,2	0,1				4,5		
Sum	100	100	100	100	100	100	100		100	100	100	100
Fuel analysis (% w/w a.r.)												
Moisture	10,2	10,9	10,8	9,8	16,0	24,2	0,0	100		1,5	5,0	7,0
Ash	7,5	0,32	13,4	2,8	6,0	7,8	0,0		100	98,5	95,0	93,0
C	40,6	44,8	38,7	46,3	41,0	28,1	80,0					
H	5,4	5,8	5,3	5,8	4,7	4,3	11,8					
O	35,8	38,0	30,1	34,4	30,1	34,4	8,2					
N	0,5	0,2	1,7	0,9	2,2	1,2	0,0					
Sum	100	100	100	100	100	100	100	100	100	100	100	100
HHV, a.r. (MJ/kg)	16,45	18,46	15,59	19,38	16,21	11,15	40,98	0	0	0	0	0
LHV, a.r. (MJ/kg)	15,06	16,97	14,19	18,61	14,81	9,65	38,48	-2,44	0	0	0	0

Table 9-1. Raw material analyses used for calculation of pellet mixtures. Ash analysis was performed by SEM-EDA. S and Cl are considered as being part of the 550 °C ash. M1-M5 are raw materials, M6-M7 binding/lubricating agents and A1-A6 are additives.

Receipt	Material (% w/w a.r.)												SUM
	Wheat straw M1	Wood M2	Grain screen M3	Sunflower M4	Sheanut M5	Molasses M6	Rape seed oil M7	H2O A1	CaO A2	Kaolin A4	CaCO3 A5	Al(OH)3 A6	
R1	94,9							4,0				1,1	100
R2	92,5							5,6		1,9			100
R3	89,8				3,0			6,0	1,2				100
R4	56,6	27,9						11,3			4,2		100
R5	54,2	26,7				4,0		10,8				4,3	100
R6	51,1	25,1				4,6	4,6	10,0			4,6		100
R7		27,7	56,4			4,8	2,9	3,4			4,8		100
R8			57,0	27,9		4,9	1,9	3,4			4,9		100
R9			57,0		27,9	4,9	1,9	3,4			4,9		100
R10			85,3			4,8	2,0	3,1			4,8		100
R11		29,5	59,8			2,0	2,0	3,8			2,9		100
R12			62,7		30,7			3,7			2,9		100

Table 9-2. Recipes used for calculation and production of pellet mixtures.

The recipes shown in Table 9-2 were based on having either straw (R1-R6) or grain screenings (R7-R12) as a main constituent. R1 through R6 has a decreasing share of straw whereas R7 through R12 has an increasing share of grain screenings. Sawdust, sunflower shells and shea nut shells were added to modify the ash quality as well as varying quantities of mineral additives. Molasses, rapeseed oil and water were added to increase productivity and hardness of the pellets. In addition, rapeseed oil increases the heating value of the mixture due to its relatively high heating value.

Table 9-3 shows the calculated compositions of the produced pellet batches based on the recipes in Table 9-2 and the material analyses in Table 9-1. Three different water contents are listed: one was determined after cooling of the pellets (at Biotechnological Institute), another was determined before combustion (at the Danish Technological Institute), and the last was calculated. The calculated values agree quite well with the determinations. In general they are a bit higher, but with R4, R5 and R6 the calculated values are much too high. In these productions a surplus of water was added in order to cool the dies of the pellet press and much of this water was probably evaporated. In Table 9-4 the fuel analysis has been calculated on dry matter basis, using the calculated moisture content. The ash contents of the pellets vary considerably (range 9-19% d.m.) whereas the lower heating values are quite constant at 16-17 MJ/kg d.m.

Ash analysis	Fuel pellet											
(% w/w ash d.m.)	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12
SiO_2	45,5	50,7	42,9	26,6	25,0	23,1	20,7	19,6	19,1	24,0	25,1	23,2
Al_2O_3	8,1	7,9	0,5	0,3	28,9	0,3	1,3	1,3	1,4	1,5	1,6	1,7
Fe_2O_3	1,0	0,9	0,9	0,6	0,5	0,5	1,6	1,5	1,7	1,8	1,9	2,0
CaO	8,0	7,3	22,4	31,9	4,9	32,9	30,1	29,4	27,4	26,7	25,8	23,0
MgO	1,6	1,5	1,5	1,0	0,9	0,9	2,4	3,0	3,0	2,7	2,9	3,6
Na_2O	0,3	0,3	0,8	0,2	1,0	1,0	1,8	1,7	1,6	1,8	1,7	1,3
K_2O	19,1	17,5	19,7	11,3	12,8	12,2	13,3	15,1	18,0	14,7	14,9	20,0
SO_3	3,5	3,2	3,7	2,1	2,4	2,3	3,5	3,9	4,3	3,9	3,9	4,8
P_2O_5	2,8	2,5	2,7	1,7	1,6	1,5	7,0	7,2	7,3	8,1	8,5	8,8
CO_2, H_2O from OH	4,9	2,8	0,0	21,4	18,8	22,5	16,1	15,2	14,3	12,3	11,2	9,3
Cl	4,9	4,4	4,8	2,9	2,9	2,7	1,8	1,8	1,8	2,1	2,1	2,0
Other	0,3	1,2	0,3	0,2	0,2	0,2	0,3	0,3	0,3	0,4	0,4	0,4
Sum	100	100	100	100	100	100	100	100	100	100	100	100
Fuel analysis												
(% w/w a.r.)												
Moisture (by Tech. Inst.)	10,6	12,9	12,5	7,5	6,5	11,7	10,6	11,2	14,0	13,1	11,8	14,8
Moisture (by Biotech. Inst.)	12,8	14,3	12,2	7,7	6,0	10,3	9,1	10,7	13,3	12,3	11,3	13,4
Moisture	13,8	15,1	15,9	20,3	20,5	19,3	13,9	13,7	15,5	13,7	14,1	15,5
Ash	8,1	8,8	8,2	8,3	8,5	8,6	12,6	13,5	14,3	16,4	11,0	13,0
C	38,5	37,6	37,3	35,5	35,1	37,0	37,9	37,9	36,4	36,0	38,5	36,9
H	5,1	5,0	5,0	4,7	4,6	5,0	5,1	5,1	4,8	5,0	5,2	4,8
O	34,0	33,1	33,2	30,9	30,9	29,8	29,4	28,6	27,4	27,5	30,1	28,1
N	0,5	0,5	0,5	0,3	0,4	0,4	1,1	1,3	1,6	1,5	1,1	1,7
Sum	100	100	100	100	100	100	100	100	100	100	100	100
HHV, a.r. (MJ/kg)	15,6	15,2	15,1	14,5	14,3	15,4	15,6	15,6	14,7	14,7	15,8	14,8
LHV, a.r. (MJ/kg)	14,2	13,8	13,7	13,0	12,8	13,9	14,2	14,4	13,3	13,3	14,4	13,4
Estimated HHV (MJ/kg), a.r.	15,8	15,4	15,3	14,5	14,4	15,5	16,0	16,0	15,2	15,2	16,2	15,3

Table 9-3. Calculated fuel pellet compositions. The estimated HHV as received is calculated for comparison, using an empirical correlation. The light grey moisture results were determined.

Fuel analysis (% w/w d.m.)	Fuel pellet											
	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12
Ash	9,4	10,4	9,7	10,4	10,6	10,7	14,6	15,6	17,0	19,0	12,8	15,4
C	44,7	44,2	44,3	44,5	44,1	45,8	44,0	43,9	43,0	41,7	44,8	43,6
H	5,9	5,9	5,9	5,9	5,8	6,1	6,0	5,9	5,6	5,8	6,1	5,6
O	39,4	39,0	39,5	38,7	38,9	36,9	34,1	33,1	32,4	31,9	35,0	33,3
N	0,5	0,5	0,6	0,4	0,5	0,4	1,3	1,5	1,9	1,7	1,3	2,1
Sum	100	100	100	100	100	100	100	100	100	100	100	100
LHV, wf (MJ/kg)	16,8	16,7	16,7	16,9	16,8	17,8	16,9	17,1	16,2	15,8	17,1	16,3
LHV, waf (MJ/kg)	18,6	18,6	18,5	18,9	18,7	20,0	19,8	20,2	19,5	19,4	19,6	19,2
LHV, at 8 % moisture (MJ/kg)	15,3	15,1	15,2	15,4	15,2	16,2	15,3	15,5	14,7	14,3	15,6	14,8

Table 9-4. Calculated fuel analysis of pellets on a dry matter basis as well as the lower heating value on water free, and water and ash free basis.

9.3. Melt area fractions

The melt area fractions obtained from the laboratory prepared (550 °C) ashes are shown in Figure 9-1 (straw based recipes) and Figure 9-2 (grain screenings based recipes).

In Figure 9-1, it can be noticed that the melting curves differ significantly in shape and amount of melt detected. R1, R2 and R3 contain the lowest shares of additive. These mixtures do also have the highest melt area fractions. R3 is similar to R1 except that approx. 1% w/w $Al(OH)_3$ was replaced with approx. 1% w/w CaO. The presence of CaO apparently lowers the melt fraction in general and enhances the "shoulder" of R1 at about 950-1050 °C. It has been found that such "shoulders" are typical for laboratory prepared straw ashes. R2 contains approx. 2% w/w $Al(OH)_3$. R4, R5 and R6 contain approx. 5% w/w of additive and are accordingly low melting.

In Figure 9-2 the melting curves are very similarly shaped, indicating that the chemical compositions of the pellets R7 to R12 are nearly identical. This is supported by the fact that grain screenings have by far the highest ash content of the raw materials and therefore dominate these mixtures. The melting fractions of R7, R8 and R9 are relatively low, while R10, R11 and R12 show higher degrees of melting. Compared to the recipes based on straw, however, the degree of melting is generally low.
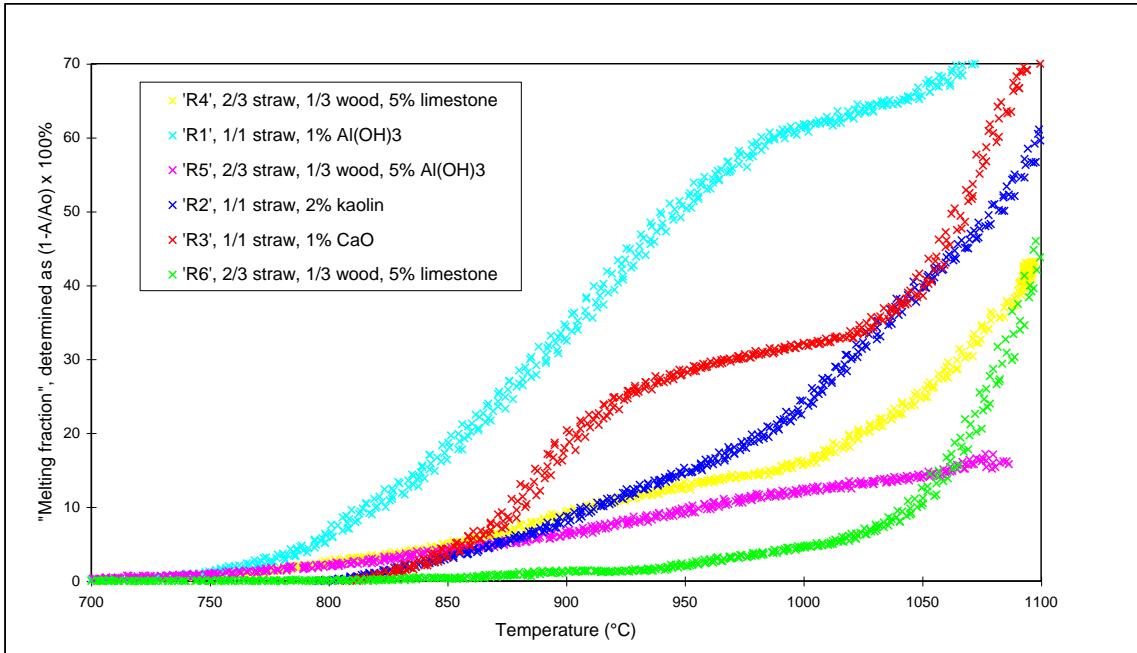
Figure 9-1. Melting curves for recipes based on straw (R1-R6).
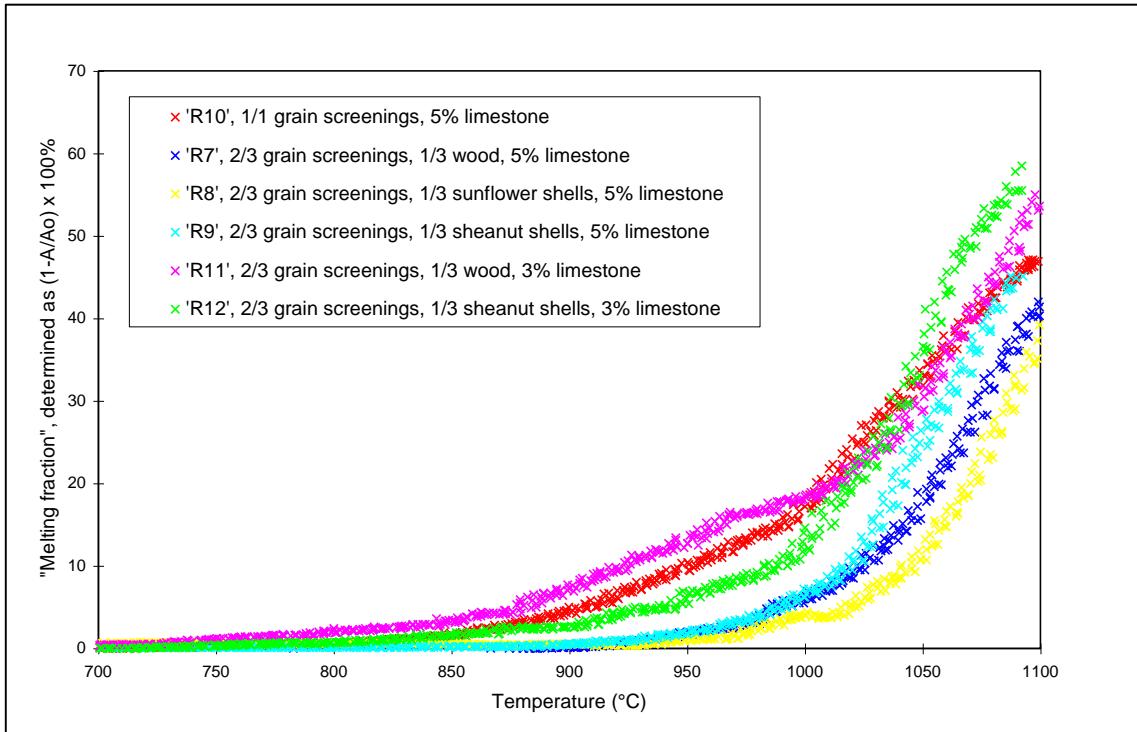
Figure 9-2. Melting curves for recipes based on grain screenings (R7-R12).

In addition to the above mentioned, the melting curves of laboratory ashes of two Reed Canary Grasses (Phalaris Arundinacea) tested during a previous study with the same 30 kW boiler were obtained. These are nearly identical and quite similar to R2. Notice the significant increase of the melt fraction at about 1050 °C. However, during the previous tests it was found that the 30 kW boiler performed very well with RCG1, producing

virtually no slags, whereas RCG2 produced lots of slags. An explanation could be that the measured "flame temperature" was reported to be 1050 °C and 1130 °C with RCG1 and RCG2, respectively. Thus, the temperature and melt fraction of the RCG2 ash may have been significantly higher than the RCG1 ash.
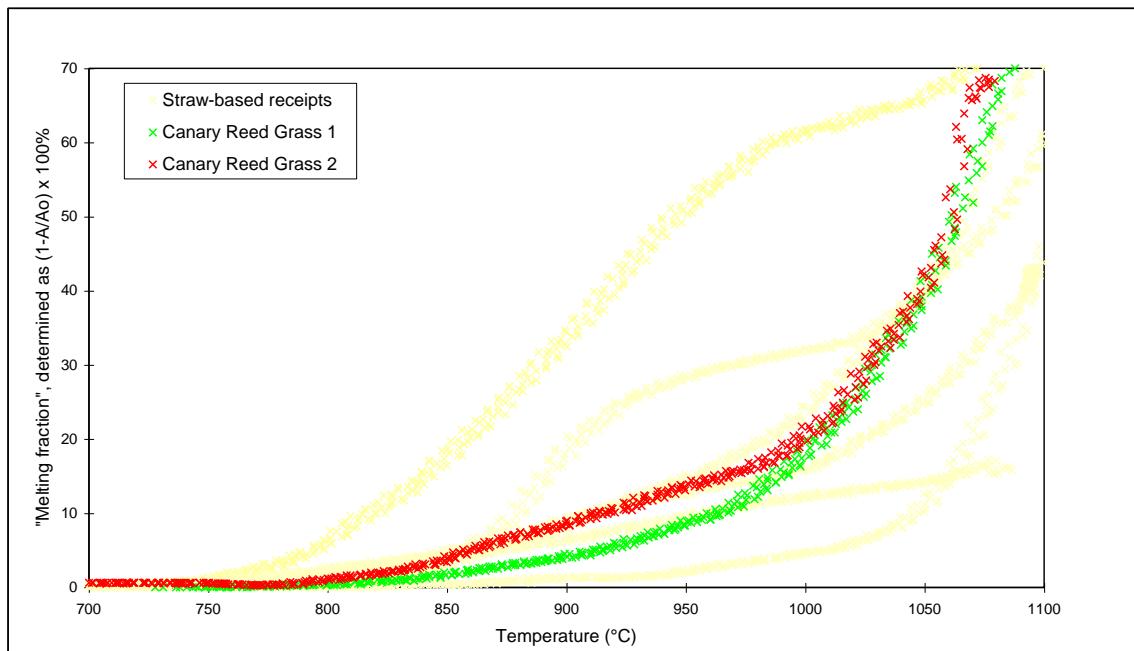
Figure 9-3. Melting curves of two Reed Canary Grasses tested in a previous project. The melting curves of the straw-based recipes tested in this project are shown for comparison.

In Table 9-5 the recipes have been categorised according to their melt area fractions in the temperature range 900 °C to approx. 1000 °C. This range is relevant as indicated from the "flame" temperature measurements obtained in the combustion tests. R6, R7, R8 and R9 have with the lowest fractions (best results), while R1, R2 and R3 have the highest fractions (worst results). The rank of the individual recipes should be taken with care due to uncertainties of the method and sample inhomogenity, but the overall picture should be clear.

Reciept	Fuel pellet	Additive	"Category"
R8	2/3 grain screenings, 1/3 sunflower	limestone, 5 %	
R7	2/3 grain screenings, 1/3 wood	limestone, 5 %	
R9	2/3 grain screenings, 1/3 sheanut	limestone, 5 %	
R6	2/3 straw, 1/3 wood	limestone, 5 %	I
R12	2/3 grain screenings, 1/3 sheanut	limestone, 3 %	
R10	1/1 grain screenings	limestone, 5 %	
R5	2/3 straw, 1/3 wood	Al(OH)3, 5 %	
R4	2/3 straw, 1/3 wood	limestone, 5 %	
R11	2/3 grain screenings, 1/3 wood	limestone, 3 %	II
R2	1/1 straw	kaolin, 2%	
R3	1/1 straw	CaO, 1%	
R1	1/1 straw	Al(OH)3, 1%	III

Table 9-5. Recipes "ranked" according to their melt area fraction at 950 °C.

9.4. Melting behaviour versus ash composition

In order to improve predictions of ash melting behaviour of fuel mixtures and the possible effect of additives it is important to study the relations between ash melting behaviour and chemical composition of the ash.

Unfortunately, in practice it is impossible to determine and represent the chemistry of ashes in a simple way. Ash composition is traditionally reported as content of "main" (approx. 1 % w/w or more) elements, typically on an oxide basis although they may not be present as such. Ternary diagrams may be suitable for graphical representation and analysis of ash chemistry and melting data if the melting behaviour is dominated by, or at least influenced by, up to three elements.

In Figure 9-3, the chemical compositions of the laboratory ashes prepared from the 12 pellet mixtures are plotted in a K_2O-CaO-SiO_2 ternary diagram on a weight basis. The two Reed Canary Grasses (RCG1, RCG2) are also included. Except from R5, the diagram accounts for 59 to 78% of the total mass. R5 has a low content of CaO (high content of Al), that is, the accounted mass drops to 38% (R5 omitted in this discussion). The weight fractions are normalised to 100% in order to represent the data in the diagram. Apparently R6 - R12 are quite similar in composition (relatively high content of CaO) and also R1, R2, and RCG2 (low content of CaO).

A database was prepared during this work, based on literature references, containing more than 150 related sets of chemical analysis data and data from the standard ISO 540 test or the like (ASTM etc.). The objective was to study the relationship between results obtained using the standard method and the chemical compositions of the ashes.

Figure 9-4 shows the Initial Deformation Temperature versus the ash composition plotted in a K_2O-CaO-SiO_2 ternary diagram. The colour of the symbols indicate the IDT, i.e. red is IDT < 800 °C, magenta is 800 °C < IDT < 900 °C etc. The compositions of R1-R12 are also shown for comparison (grey symbols as the IDT was not determined). Due to the uncertainty of the standard method, analysis results etc., some data may not be correctly shown in the diagram. However, due to the large number of data an indicative picture is obtained. It is indicated from the data in Figure 9-4 that R1 and R2 (R5 omitted) fall in a region where a low IDT may be expected, the composition of R3 is "intermediate", and R4 and R6-R12 should have higher IDT.

In the glass making industry and among ceramics it is considered practical to work with a ternary diagram with the three points of the triangle being amphoteric, acidic and basic. The definition of these groups is similar to the Brønsted acid-base definition, stating that any compound that dissolves in water producing an excess or deficiency of hydrogen ions is an acid or a base, respectively. Thus, SiO_2 is an acid whereas Na_2O, K_2O, MgO and CaO are bases. Al_2O_3 is strongly amphoteric whereas Fe_2O_3 is weakly amphoteric. The reason why this works may be that, in general, SiO_2 is the network former of glass, basic oxides are network modifiers (have disruptive effects) and amphoteric oxides can be considered as intermediates. The amphoterics Al and Fe(III) are typically found in minerals being charge balanced by modifier ions. In Figure 9-5 such a diagram is shown with same data as mentioned above. It has the advantage that typically most of the mass of the ash may be represented. The R5 ash is correctly placed apart from the other ashes, having an atypical high content of Al_2O_3. Besides this, similar comments apply to Figure 9-5 as to Figure 9-4.
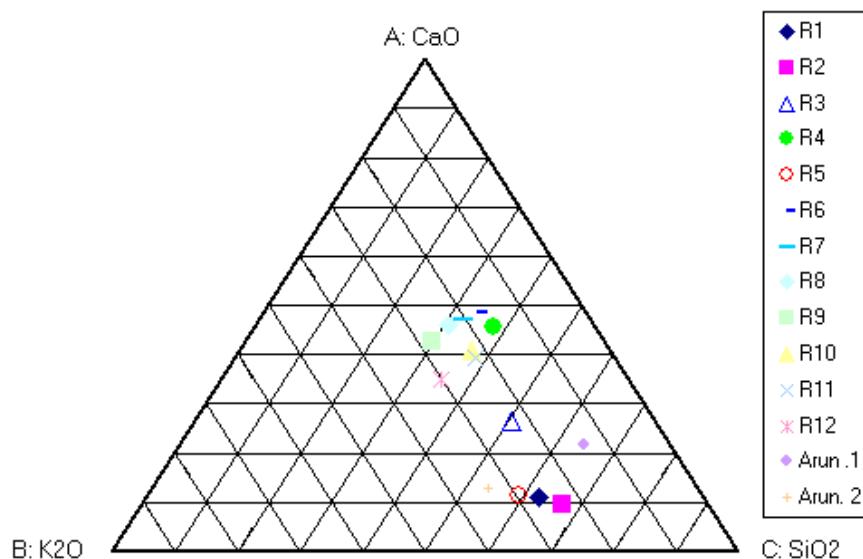
Figure 9-4. Positions of R1-R12 in the K_2O-CaO-SiO_2 system. Two Reed Canary Grasses tested in a previous project are also shown for comparison (Arun 1 & Arun 2).
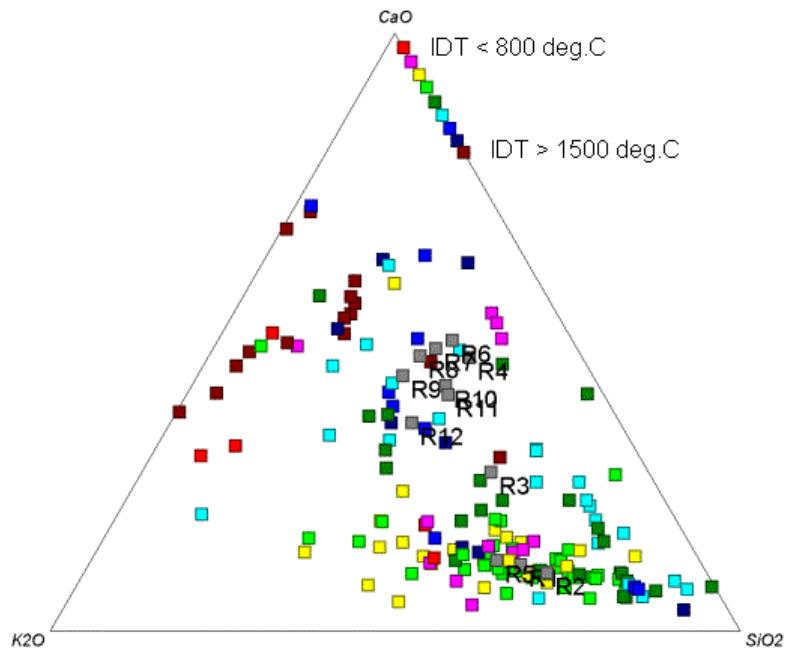
Figure 9-5. Initial deformation temperatures of laboratory prepared ashes (data taken from literature). The positions of R1-R12 are shown for comparison.
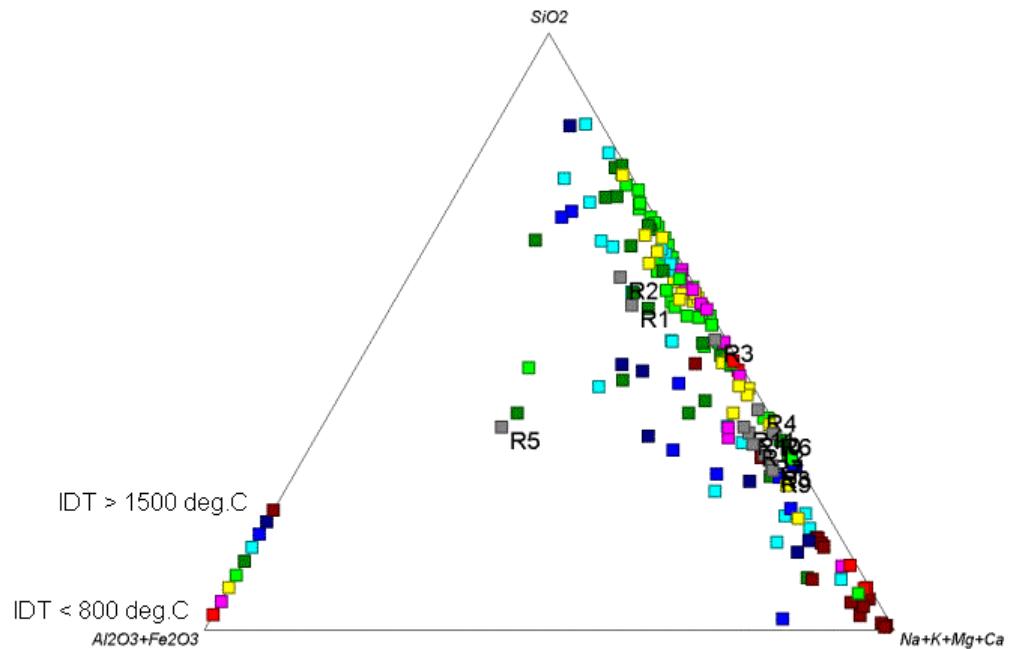
Figure 9-6. Similar data as in Figure9-4 depicted in the amphoteric-acid-base ternary diagram (Fe₂O₃ are considered as an amphoteric oxide).

9.5. Slagging indices

The indices discussed in Chapter 4 have been calculated (on dry ash basis) for the recipes prepared in this work. The results are shown in Figure 9-7. Except from R1, R2 and R5, the ashes are basic with basic/acid ratios above 1. According to the R_S and R_F indices, R9 and R12 should produce severe slagging and fouling, whereas R5, R1 and R2 should be more moderate in this respect. The alkali to silicon ratio shows a similar trend. R5, R1 and R2 do also have the highest silicon ratio, indicating high melt viscosity and low slagging propensity. Notice that R5 is atypical and resembles coal ash with its high Al content. All recipes have very high alkali to energy contents. With respect to slagging, the above indications are conflicting with the results from the combustion tests in the 30 kW boiler.
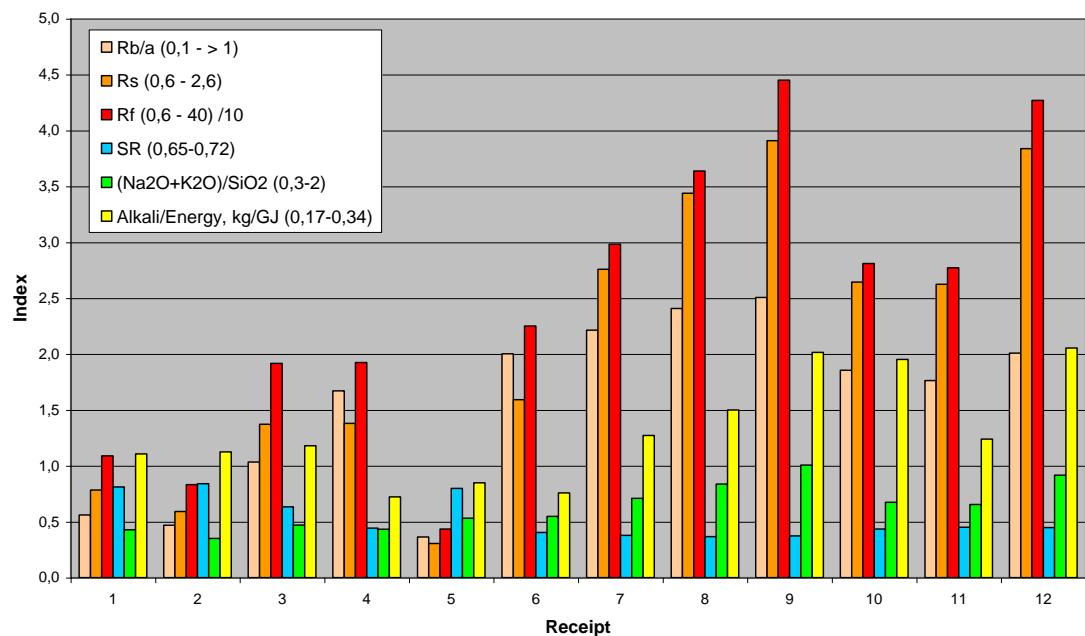
Figure 9-7. Various slagging/fouling indices as function of pellet recipe.
Typical ranges of variation are given in parenthesis.

9.6. Mass balance of ash of the combustion tests

For each of the combustion tests R5-R12, a mass balance of ash was established. The total mass of residue (bottom ash/slag) was determined after each test, and random samples were milled and glown at 550 °C for determination of ash content. The quantity of ash deposited in the initial 0.4 m (from the hot gas end) of a single flue gas tube was determined by scraping off the deposit and weighing. The total quantity of deposit in the tube sections was then estimated assuming the deposition rate to be constant during each test run. The metal temperature was approx. 78 °C in all tests. The total particle emission from the unit was determined as well.

The results are shown in Table 9-6. The fuel consumption was about 8 kg/h (dry) in each test. For calculation of dry mass, the moisture contents determined by Danish Technological Institute were applied. It appears from Table 9-6 that some material is missing all balances. Due to the uncertainties of sampling residues and estimating the deposition rate, the results must be taken with care. However, it seems unlikely that material should be missing in all tests, but no clear explanation has been found.

RECIEPT	Fuel	Ash	Ash flow IN	Residue	Ash content	Glown ash	Part. emission	Deposition	Ash flow OUT	DEV. %
	kg/h, dry	%w/w, dry	kg/h	kg/h, dry	% w/w, dry	kg/h, dry	kg/h	kg/h	kg/h	
R5	8,32	0,106	0,88	0,99	74,2	0,73	0,023	0,0153	0,77	-12
R6	7,68	0,107	0,82	0,65	88,2	0,57	0,024	0,0108	0,61	-26
R7	7,51	0,146	1,10	0,82	84,6	0,69	0,016	0,008	0,72	-35
R8	7,64	0,156	1,19	0,9	77,9	0,70	0,022	0,0143	0,74	-38
R9	7,65	0,17	1,30	1,06	80,9	0,86	0,025	0,0143	0,90	-31
R10	7,65	0,19	1,45	1,05	85,8	0,90	0,02	0,0088	0,93	-36
R11	7,57	0,128	0,97	0,92	81,8	0,75	0,012	0,0125	0,78	-20
R12	8,26	0,154	1,27	1,34	64,1	0,86	0,022	0,0068	0,89	-30

Table 9-6. Mass balances of ash for the combustion tests (R5-R12). The results should be taken with care, especially the ash content of the residue and the estimated deposition rate.

10.   Fouling Tests at Brigham Young University

By Helle Junker, Tech-wise

10.1.   Objective

It is the aim of the project to document and develop quality declarations of biofuel pellets produced from a mixture of biomass waste products with binding agents and anti-slagging additives. In the future, the market for mixed pellets is expected to increase – both for pellets of indigenous origin and for imported ones. Since the prices may come to affect the power plant sector, it is relevant to examine the behavioural aspects of mixed pellets when subjected to combustion conditions as found in a power plant setting.

10.2.   Choice of BYU as a partner

The original application was based on a preliminary co-operation arrangement with Sandia National Laboratories (SNL) to test the biofuel mixtures under power plant conditions. However, a severe limitation of the biomass activities at SNL was expected and it was realised that SNL would probably not be able to fulfil their commitment. It can be a difficult task to find a scientific partner for a series of tests when the framework has already been detailed. The tests are to match the research objectives of the research institution concerned to allow them to fund their part of the project. Finally, an agreement was made with Brigham Young University (BYU) to have the tests carried out in close co-operation with Prof. Larry Baxter, Prof. Dale Tree and their team at BYU. Larry Baxter used to be at SNL and Tech-wise have enjoyed a prosperous partnership on several projects.

The description of the method applied and the results achieved is a summary of the descriptions in [1] and [2].

10.3.   Method

Test facility

The tests were conducted at the recently rebuilt multifuel flow reactor (MFR) at BYU. The MFR is a down-fired reactor with a reaction length of ~ 2 meters before the sampling position of the deposits. The reactor's inner diameter is 12 cm.

The facility was heated partly by natural gas, and the simulations of the test represent co-firing of the agricultural residues in a power station fired with natural gas. The natural gas firing was needed to keep the temperature in the reactor above 850 °C in the zone with the deposition probe. Flame stability was also enhanced and fuel-to-fuel variations in flame temperature were decreased by combining methane with the solid fuels in equal proportions as measured by O_2 consumption. During the tests, the residence time for the biofuels was kept at approx. 1 second, which is similar to power

plant conditions, and the oxygen content was 4-5%. The air-cooled sampling probe was maintained at 450-550 °C surface temperature during each test All tests were run for 30 minutes.

Test matrix

The tests conducted at the MFR at BYU both aim at

- evaluating the fuel mixtures tested at Danish Technological Institute and

- carrying out some linearity investigations to see if interactions took place between the inorganics in the fuel.

Therefore, the tests include:

- Investigations of R1-R12

- Investigations of pure biofuels: Straw, wood, grain screenings, sunflower shells, shea nut shells and sugar beet pulp

- Linearity investigations between mixtures of biofuels.

The results of the tests from which conclusion can be made are: Photos of the deposits formed, deposit mass accumulations, CCSEM analysis of the deposits and chemical analysis of the deposits.

10.4.   Preliminary results and conclusions from the first tests

The results falls into two categories:

1. Quantitatively measured ash deposition rates

2. Effects of fuel ash composition on corrosion

Not all of the test results conducted by now have finished the examination by CCSEM, so the data for discussion of the corrosion data are less than for the ash deposition rate.

10.5.   Quantitatively measured ash deposition rates

A suite of six biomass fuels incorporating a wide range of organic and inorganic compounds were used to investigate blending effects on the deposition rate. The fuels included straw, grain screenings, sawdust, sunflower shells, shea nut shells and sugar beat pulp. All of the fuels were prepared and shipped from Denmark. The test matrix included measured deposition rates on each of the six fuels shown and on eight of the fuels blends. The fuel blends were selected by mixing 50% by mass of the two fuels

available in the largest resources as agricultural residues and expected to have the highest ash deposition rates (straw and grain screenings) with 50% by mass of each of the four fuels available in the smallest quantities and initially expected to have the lowest deposition rates (sawdust, sunflower shells, shea nut shells and sugar beat pulp).

Industrial facilities designed to use biomass fuels must deal with a large variance in the ash deposition rates. These rates vary as much as two orders of magnitude. Deposition lowers facility efficiency and increases operational costs.

The differences in predicted and measured amounts of ash flux prove that ash loading and fly ash particle size are not the only factors that influence deposition rates. Other mechanism and factors besides inertial impaction must be accounted for in order to predict the deposition rates precisely. Variance between predicted and measured ash amounts is also attributed to the difference in capture efficiency for the various fuels and fuel blends. Particle size and composition, deposit shape and chemical interaction between fuels all influence capture efficiency.

Differences between the major agricultural residues (straw and grain screenings) and the fuels that did not follow predicted deposition rates are attributed to differences in chemical makeup. Sugar beet pulp is washed thoroughly before combustion and contains very little alkali metals. This means that sugar beet pulp forms ash particles containing mainly silica. Ash particles made mainly of silica tend to bounce off impaction surfaces. Sawdust contains very little inorganic material and therefore creates small fly ash particles. Sawdust ash deposition is probably attributed mainly to eddy impaction.

Some variance in predicted and measured data, especially in cases of mixed biomass fuels, is attributed to various chemical reactions. Of course some variance between predicted and measured values is due to experimental error. These tests suggest that alkali and chloride components in fuels contribute to mass accumulation by forming condensate layers on heat transfer surfaces or reacting with silica to form alkali silicate particles. As sulfur and silica amounts increase in fuels, the tendency to react with alkali metals decreases. For instance mixtures between straw and sawdust and grain screenings and sawdust deposited less than predicted because of such chemical interactions in inorganic materials.

In general, interpolated predictions of ash deposition over predict the amount of ash collecting on surfaces. However, the agreement between predicted and experimental data is reasonably good for most blends. This could be an indicator for only limited interactions between the blended biofuels. However, more experiments need to be carried out in order to minimize variations due to experimental error.

10.6. Effects of fuel ash composition on corrosion

The data presented here are from the tests carried on the following suite of biomass fuels:

1. 100% sawdust
2. 100% straw
3. R4 (1/3 sawdust + 2/3 straw + 5% $CaCO_3$)
4. R6 (1/3 sawdust + 2/3 straw + 5% $CaCO_3$ + 5% rapeoil + 5% molasses)

The test results are discussed based on data from the CCSEM analysis.

The straw deposits produced potassium and chlorine layers at the ash-metal interface, with no silica or sulfur evident. This indicates the presence of a relatively pure potassium chloride. Potassium and silica occur separately in straw and not as a compound such as (K_2SiO_4). However, during straw combustion, potassium reacts with silica to form silicates. This reaction is temperature dependent; therefore, it is a strong function of sampling probe surface temperature. Here, it seems like even at a temperature of ~ 450 ^{o}C, some of potassium reacts with silica to form potassium silicate.

Sawdust produces much less deposit than straw. Unlike straw, the K and Cl are not correlated in the SEM cross section maps. However, potassium and silica are correlated. This can be explained by looking at sawdust composition. It contains only 0.2% w/w chlorine but almost same amount of potassium as that in straw (as a fraction of ash). Therefore, the lack of chlorine possibly favored the reaction between potassium and silica. Calcium reacted with both silica and chlorine, but to a minor extent.

The fuel blends R4 and R6 exhibit similar composition except that rape (colza) oil and molasses were added to R6 to enhance pellet properties. These fuels comprise 1/3 sawdust, 2/3 straw and 5% $CaCO_3$. In elemental maps of R4 and R6, potassium and chlorine layers appear at the ash-metal interface. In addition, potassium and silica were found correlated. But when compared to 100% sawdust and 100% straw, the potassium chloride layer was found more prominent than that in sawdust ash but less distinct than that in straw ash. In R4, potassium and calcium silicates are present in significant amounts, indicating more substantial interactions of silica with alkali and alkaline earth metals. No effect of the additives in R6 is evident or was expected in these results.

Blends of biomass fuels produce products that react in ways that are not always proportional to the blend ratio. In particular, sulfur, alkali, and chlorine from different sources may react to form products that are not well represented as averages of the products formed from the pure fuels. However, all of the fuels we have observed follow patterns that are predictable, at least qualitatively.

In general, biomass fuels and fuel blends containing chlorine and available alkali, but with minor amounts of sulfur, produce ash deposits that feature alkali chloride layers on the heat transfer surface. Such deposits are potentially corrosive in addition to accelerating deposit growth.

10.7. References (see Appendix 2 and 3)

[1] David Dunaway, Shrinivas Lokare, Doug Rogers, David Moulton, Helle Junker, Dale Tree, and Larry Baxter: ”Quantitatively Measured Ash Deposition Rates for a Suite of Biomass Fuels”. Presented at 2002 Spring Meeting of Western States Section of The Combustion Institute.

[2] Shrinivas Lokare, Dave Moulton, Helle Junker, Dale Tree, and Larry Baxter: ”Effects of Fuel Ash Composition on Corrosion”. Presented at 2002 Spring Meeting of Western States Section of The Combustion Institute.

11.   Declaration for Biofuel Pellets

By Lars Nikolaisen, Danish Technological Institute

11.1.   The European standardisation process for biofuels

In the project application a declaration for biofuel pellets was suggested. The idea was to make a proposal for a declaration in order to meet the consumers' need for information about the properties of the biofuel pellets. In the meantime, a European standardisation process for biofuels has been initiated, and due to this, a proposal for a declaration in this specific project makes no sense. In a few years, the standardisation activity will result in a number of standards which will ease the international trade with biofuels and make it possible to define biofuels producing green electricity. Below - in short terms - a status is made for the standardisation activity.

In 1999, a preliminary standardisation activity for biofuels was initiated in CEN/TC/WG108 Solid Biofuels, promoted by the Technical Board (BT) in CEN (European Committee for Standardisation). The purpose with WG108 was to create a platform for a technical committee which should elaborate standards for biofuels.

WG108 was established with members from 15 European countries (Austria, Belgium, Denmark, France, Germany, Greece, Ireland, Italy, Holland, Norway, Portugal, Spain, Sweden, Switzerland and England) with Christian Lenander, Sweden, as chairman. The report (document N96) from WG108 describes a working programme for a technical committee which shall - with a EU mandate - prepare a European standard for biofuels.

The working programme outlines that the technical committee shall elaborate standards within the following fields:

1. Terminology, definition and descriptions
2. Fuel specification, classes and quality assurance
3. Sampling and sample reduction
4. Physical/mechanical test methods
5. Chemical test methods

The working programme defines that peat and waste (household waste, demolition woods, old railway sleepers etc.) are not part of the standardisation activity.

Regarding waste a task force was established (CEN/BT/Task Force118 Solid Recovered Fuels). The task force shall prepare a working programme for a technical committee for waste.

11.2. CEN mandate for the standardisation activity

Regarding biofuels a technical committee (CEN/TC 335 Solid Biofuels) was established. The first meeting was held in Stockholm on 30 - 31 May 2000. The chairman is Birgit Bodlund, Vattefall, Sweden. EU has given CEN a mandate for the standardisation activity with biofuels. The main content of the mandate is listed in the following:

The absence of European standards is a major barrier to develop the market for solid biofuels. A market which is necessary for the European Union to reach its targets for the deployment of bioenergy. The lack of standards in the field of solid biofuels should be complemented as soon as possible. The foreseen standards should be drafted under such a structure that they would provide adequate and clear delineation among the various types of fuels, their origin and their fitness for use in specific applications. The standards structure should give the market and the legislative authorities the possibility to distinguish between renewable and fossil fuels. The standards shall define sampling and measuring procedures for those pollutants and impurities that are expected to be present in the biofuels. This will allow regulatory authorities and end users to assess the environmental aspects of solid biofuels combustion. For this purpose, a clear and definite distinction must be made between systems of fuel classes for solid biofuels.

Standardisation of solid biofuels will help to regulate the market and to provide confidence to fuel producers and fuel users. Standards on solid biofuels with respect to quality and properties will make it possible to find the optimum utilisation of different biofuels with respect to protecting the environment. In addition, standards on solid biofuels will improve the efficiency of biomass utilisation because the users will be able to procure fuels of a quality corresponding to the specifications of their equipment

This mandate may only consider biofuels originating from the following sources:

- *Products from agriculture and forestry*
- *Vegetable waste from agriculture and forestry*
- *Vegetable waste from the food processing industry*
- *Wood waste, with the exception of wood waste that may contain halogenated organic compounds or heavy metals as a result of treatment, and treated wood originating from building and demolition waste*
- *Cork waste*

For Solid Biofuels 24 standards need to be written. This will take place in 5 working groups (WG1-WG5) established under guidance of Technical Committee 335. The working groups are:

WG1: Terminology, definitions and description. Convenorship (Chairman): Germany
WG2: Fuel specification, classes and quality assurance. Convenorship: Finland
WG3: Sampling and sample reduction. Convenorship: United Kingdom
WG4: Physical/mechanical test methods. Convenorship: Sweden
WG5: Chemical test methods. Convenorship: Holland

11.3. Fuel specification and classes

Working Group 2 released document N50-draft in April 2002. The document describes "Fuel specification and classes", and in Table 5 properties for pellets are listed. Table 5 is listed below. Compared to this report, information about deslagging additives is missing. Information about deslagging additives should also include an evaluation of parameters as in Table 8-3. In this table there is an evaluation of 4 parameters (for small-scale boilers): Slag in the ash, fixed slag in the combustion chamber, dust fouling in the boiler and combustion quality. Pressing aids are binding agents and lubricants as used in this project (molasses and rapeoil).

A. Master table		
Origin: According to Table 1.		Woody Biomass (1), Herbaceous biomass (2), Fruit biomass (3).
Traded Form (see Table 2):		Pellets

<table>
<tr><td rowspan="45">N o r m a t i v e</td><td colspan="3">Dimensions (mm)</td></tr>
<tr><td></td><td>Diameter (D)</td><td>Length (L)</td></tr>
<tr><td>D06</td><td>≤ 6 mm</td><td>≤ 5 times diameter</td></tr>
<tr><td>D08</td><td>≤ 8 mm</td><td>≤ 5 times diameter</td></tr>
<tr><td>D10</td><td>≤ 10 mm</td><td>≤ 5 times diameter</td></tr>
<tr><td>D12</td><td>≤ 12 mm</td><td>≤ 4 times diameter</td></tr>
<tr><td>D25</td><td>≤ 25 mm</td><td>≤ 4 times diameter</td></tr>
<tr><td colspan="2">Moisture (weight % as received)</td><td></td></tr>
<tr><td>M08</td><td>≤ 8 %</td><td></td></tr>
<tr><td>M10</td><td>≤ 10 %</td><td></td></tr>
<tr><td>M20</td><td>≤ 20 %</td><td>Only for large-scale use and co-firing purposes</td></tr>
<tr><td colspan="2">Ash (weight % of dry matter)</td><td></td></tr>
<tr><td>A0.7</td><td>≤ 0.7%</td><td>To be modified according</td></tr>
<tr><td>A1.5</td><td>≤ 1.5%</td><td>To new standard in WG4</td></tr>
<tr><td>A6.0</td><td>≤ 6.0%</td><td></td></tr>
<tr><td colspan="2">Sulphur (weight % of dry matter)</td><td></td></tr>
<tr><td>S0.05</td><td>≤ 0.05%</td><td></td></tr>
<tr><td>S0.08</td><td>≤ 0.08%</td><td></td></tr>
<tr><td>S0.10</td><td>> 0.10%</td><td></td></tr>
<tr><td colspan="2">Mechanical durability</td><td>(Abrasion weight of fines)</td></tr>
<tr><td>DU2.3</td><td>≤ 2.3%</td><td>Based on Ligno Tester</td></tr>
<tr><td>DU5.0</td><td>≤ 5.0%</td><td></td></tr>
<tr><td>DU10.0</td><td>≤ 10.0%</td><td></td></tr>
<tr><td colspan="2">Pressing aids (w-%)</td><td></td></tr>
<tr><td colspan="2">Type and content of pressing aids</td><td>Amount and type to be stated</td></tr>
<tr><td colspan="2">Nitrogen, N (w-% of dry matter)</td><td></td></tr>
<tr><td>N0.5</td><td>≤ 0.5%</td><td>Has only to be stated for chemically treated or</td></tr>
<tr><td>N1.0</td><td>≤ 1.0 %</td><td>used wood (1.3 and 1.2.2)</td></tr>
<tr><td>N3.0</td><td>≤ 3.5 %</td><td></td></tr>
</table>

<table>
<tr><td rowspan="6">Informative</td><td>Net calorific value (MJ/kg as received) or energy density, E_{ar} (kWh/kg)</td><td>Recommended to be stated at the retail level</td></tr>
<tr><td>Bulk density (kg/m^3 loose)</td><td>Recommended categories (Bd550, Bd600, Bd650, Bd750)</td></tr>
<tr><td>Chlorine, Cl (weight of dry matter, %)</td><td>Recommended to be stated as a category (Cl0.03, Cl0.07 or Cl0.1)</td></tr>
<tr><td>Nitrogen, N (weight of dry matter, %)</td><td>Recommended categories (N0.5, N1.0 or N3.0)</td></tr>
</table>

Table 11-1. Specification of properties for pellets. Copy of CEN/TC 335/WG2 N50 Draft, table 5. Only chemically treated biofuels that are included in the scope are to be considered, i.e. wood waste which may contain halogenated organic compounds or heavy metal as a result of treatment with wood preservatives or coating, are not included.

The most important regulation on biomass fuel in Denmark is the *Danish Act No. 638 of July 3, 1997* on biomass waste. The act lays down the regulations governing solid biomass for combustion and includes waste from agriculture, forestry and companies working with biomass, e.g. sawmills and furniture manufacturers. Exclusively biomass included in the attachment of Act no. 638 is exempt from the ordinary Danish waste regulations which means that it is also exempt from the waste disposal tax. It is anticipated (see Table 11-2 no. 16) that the biomass mixtures in this report are still biomass as defined in Act no. 638.

1	**Raw wood**, including bark, forest wood chips and untreated milled chips	9	**Untreated grain and seeds**
2	**Clean wood**, including shavings and saw dust, not containing adhesives, lacquer, paint, varnish, impregnants (besides any mill stamps etc.), foil, laminates, nails, screws, fittings, etc.	10	**Untreated cotton and flax**
3	**Wood waste** from the production and treatment of clean, laminated wood, with an adhesive content (phenol-resorcinolresin, polyvinyl acetate resin, urea-formaldehyde resin, poly-urethane resin, and melamine-urea-formaldehyde resin) not exceeding 1% on dry weight basis.	11	**Lolly sticks** with a content of paraffin approved for use in foods not exceeding 1% on dry weight basis.
4	**Straw** (including baling cord from straw bales)	12	**Green pellets** (dried grass, clover etc.)
5	**Kernels** and **seeds** from fruits and berries.	13	**Malt**
6	**Fruit residues** (dry parts of fruits)	14	**Thatched roofing**
7	**Nut** and **seed shells** (including grain and seed screenings)	15	**Tobacco waste** in the form of whole or broken tobacco leaves, tobacco stalks, etc.
8	**Untreated cork**	16	**Fuel pellets** or **fuel briquettes** produced exclusively from wastes in this attachment.

Table 11-2. Biomass exempt from tax included in the attachment to the Danish Act no. 638