University of Strathclyde

Feasibility Study: Grain-dust Burner

MSc Energy Systems and the Environment

THESIS

Kirsten Hamilton 2005/2006

Abstract

The aim of the project was to investigate the feasibility of burning grain-dust in order to provide a direct source of heat in a conventional grain dryer, thereby replacing the traditional diesel fuel source.

Grain drying organisations produce large quantities of fine grain-dust during their drying operations and as this grain-dust is likely to have high calorific values to similar to straw and grain, it could be used as a fuel. A grain-dust burner could potentially be used to replace the oil burners that are used to dry the grain thereby reducing fuel costs.

The project examines some of main disadvantages of utilising biofuels such as ash-related problems which affect emissions and cause internal plant problems such as slagging, deposit formation and corrosion. Straw, cereal, grass and grain-ashes start to sinter and melt at significantly lower temperatures than wood fuels. However grain has a much lower ash content compared to straw, and therefore has less slagging problems.

Following the analysis of a variety of dust burners, the LMB Multifuel Burner which is manufactured by LBE in Germany, was selected for further investigation.

As grain-dust is not currently a recognised biofuel, no data existed for the chemical and physical properties of grain-dust. Its properties were assumed to approximate the behaviour of barley straw and grain, but testing and analysis was necessary to verify this. In addition, samples of the grain-dust from Highland Grain were sent to LBE for analysis and feasibility tests.

The corroborated analysis established that in an average sample of grain-dust, 30% of mass is made up of straw, chaff and husk; whilst 70% of the mass of is crushed grain, very small husk/straw and what was latterly determined to be a large amount of dirt. The analysis determined that grain-dust had a 1-3 MJ/kg difference in energy output (at normal moisture content) compared to wood dust. However the particle distribution of the grain-dust is significantly larger that wood dust, and will either need to be milled or sieved if it is to be used in a dust burner. As the ash content of grain-dust is significantly higher than the recommended value for dust burners, a higher proportion of grain included in the grain-dust would reduce the ash content. In spite of this, the ash softening temperature for grain-dust is up to 200°C lower than the recommended value and this poses significant slagging problems in the dust burner.

Initially it was hoped that grain dust burner could be used to provide heat directly to the grain driers. However information from LBE in the concluding stages of the project indicated that a vertical burner installation in a big combustion chamber, with ash blower and an ash screw at the bottom would be more suitable. The burner would then be used to drive a boiler, i.e. an indirect heating method.

Recommendations for further work in this area include research into whether to take the suggestions of LBE forward and employ their system into the current drying system at Highland Grain and an evaluation of the economic and practical viability of the proposal.

This feasibility study was suggested as a topic for investigation by the Campbell Palmer Partnership Ltd and work was carried out in collaboration with Highland Grain Ltd and East of Scotland Farmers Ltd (EOSF).

Acknowledgements

- Sincere thanks go to David Palmer and all at the Campbell Palmer Partnership for providing the project topic, and then assisting me so readily with their time, information and encouragement throughout the course of this project
- Thanks go to Robert Mclean for his supervision of the project over the duration of the project and for taking the time to thoroughly read my first draft
- I am extremely grateful to Dr Paul Strachan for assisting me in planning, paperwork and negotiations with the Chemistry department on my behalf
- Sincere thanks go to Simon Barry of highland Grain Ltd for giving up considerable time to discuss various aspects of drying facilities and for sending a number of large samples to Germany for analysis at my request and thanks also go to Keith for giving me such an enjoyable and informative tour around Highland Grain facilities.
- Thanks go to East of Scotland Farmers Ltd (EOSF) for providing samples of grain-dust
- Thanks go to Dr Christine Davidson of the Chemistry Department for giving up time to discuss various methods of analysis, pointing me in the right direction and for lending me a selection of sieves
- I am very grateful to Yvonne Cruickshank of the Chemistry Department who was so willing to help locate sieves, a sieve shaker, all the necessary equipment and paperwork which turned out to be a much more time-consuming process than anticipated
- Thanks go to Margaret Adams of the Chemistry Department for completing the microanalysis and the grain-dust samples
- Thanks go to Sheila McCulloch and Alan Kennedy of the Chemistry Department for all their assistance, time and use of equipment needed to complete the calorific experiments
- Thanks go to James Kelly of the MechEng department for so assisting me with the furnaces when analysing the moisture and ash content of the grain-dust content
- Thanks go to Dr. Dr Roger Williams of HGCA for information on calorific values
- Thanks go to Ralph Roth for LBE in Germany for so readily contacting me, answering questions and completing the analysis of grain-dust samples
- Thanks go to Stuart Spence for inspiration, helping to generate concepts, and providing technical advice
- Thanks go to Paul Hamilton for his patience, encouragement and support.

Table of Contents

Index of Figures

Index of Tables

Abbreviations:

ELEMENTS	
Ag	Silver
Al	Aluminium
As	Arsenic
C	Carbon
Ca	Calcium
Cd	Cadmium
Cl	Chlorine
Co	Cobalt
Cr	Chromium
Cu	Copper
Fe	Iron
H	Hydrogen
Hg	Mercury
K	Potassium
Mg	Magnesium
Mn	Manganese
N	Nitrogen
Na	Sodium
Ni	Nickel
O	Oxygen
P	Phosphorus
Pb	Lead
S	Sulphur
Si	Silicon
Sn	Tin
V	Vanadium
Zn	Zinc

COMMON COMPOUNDS	
H_2O	Water
CO	Carbon monoxide
CO_2	Carbon Dioxide
O_2	Oxygen
SO_X	Oxides of Sulphur, principally as SO_2
NO_X	Oxides of Nitrogen, principally NO and NO_2
HCl	Hydrochloric acid

BASIS	
ar	as received, as sampled or as delivered
ad	air-dried, as determined
db	dry or dry basis
daf	dry, ash free
% wt	Percentage of total mass

1) Introduction

1.1 Project Definition

1.1.1 Brief

In the whisky industry, barley grain is dried to be used either as feed grain or malting barley. Grain dryers traditionally use direct-fired oil burners to heat air to a range 60°C to 100°C for grain drying. However, grain drying organisations produce large quantities of fine grain-dust during their drying operations and this dust is usually sent to landfill sites. Grain and grain straw have high calorific values and consequently grain-dust is likely to have similarly high values and therefore could be used as fuel.

A grain-dust burner could be potentially be used to replace the traditional oil burners that are used to dry the grain and thus reduce fuel costs substantially.

1.1.2 Aim

The aim of the project was to investigate the feasibility of burning grain-dust in order to provide a direct source of heat in a conventional grain dryer, thereby replacing the traditional diesel fuel source.

1.1.3 Objectives and Deliverables

The main objectives of the project were broken up into the following sections:

i) Research
ii) Analysis
iii) Design and integration

The project deliverables evolved over course of 4 months, however on the whole adhered closely to the original objectives (see Appendices 10.1) laid out at the beginning of the project. The final deliverables are as follows:

Research

- The chemical and physical characteristics of grain and straw and their potential correlation with grain-dust.

- Comparable technologies and techniques used to burn coal dust or biofuels and their relevance.
- The key issues associated with the direct burning of dust. This included a detailed examination of the slag formation, ash and emissions.

Analysis

As grain-dust is not currently a recognised biofuel, no data existed for the chemical and physical properties of grain-dust. Its properties were assumed to approximate the behaviour of barley straw and grain, but testing and analysis was necessary to verify this.

- The particle size distribution of the samples was calculated experimentally and then separated into three sub-samples for a series of chemical and physical analysis
- The calorific values of the 3 separate samples were established experimentally, in addition to moisture and ash content, and the content of C, H, N, O and Cl
- The chemistry of the combustion of grain-dust was established through comparable research and the results of the tests

Design and Integration

The following areas will be covered in the Design and Integration section:

- The extent to which grain-dust burning had been undertaken was established and relevant patents were highlighted
- A suitable dust burner was selected through careful analysis of the available models.
- The dust flow rates/throughputs necessary to match the power generated by the oil burners was calculated and associated issues were highlighted
- Using the chosen model, suggestions of how the grain-dust burner would be integrated into the grain dryer were made
- The feasibility study concluded by summarising the relevant information and by making recommendations on how the design and integration could be taken further.

1.1.4 Conclusion Summary

This feasibility study was suggested as a topic for investigation by the Campbell Palmer Partnership Ltd and work was carried out in collaboration with Highland Grain Ltd and East of Scotland Farmers Ltd (EOSF).

Two years ago the cost of oil was about 1.6 pence/kWh, at the time of writing it was costing 3.65 pence/kWh due the increase of fuel in recent years. At current grain prices, and using the calorific value of grain, the price of grain can be calculated to be about 1.8 pence/kWh, thus equating to the price of oil 2 years ago. Therefore if grain-dust provided a viable fuel option, it would not only reduce fuel costs dramatically by using the dust as a fuel, it would also be cheaper to mill excess grain in order to utilise it as grain-dust fuel, should larger quantities of grain-dust be needed.

1.2 Background

1.2.1 Biomass and Bio-energy

Plant matter, or biomass, has also long served as one of the primary energy forms utilised by humans for essential activities (Jenkins et al, 1998). During photosynthesis, plants convert radiant energy from the sun into chemical energy in the form of biomass (Braymo, 2005). This potentially extractable chemical energy is referred to bio-energy. The sun's energy incident on top of atmosphere is enormous, over 10^{17}W and of this, plants collect and utilise 0.02%, producing annual energy storage of 10^{21}J (Jenkins et al, 1998). Thus, biomass provides a vast resource for potential energy exploitation.

The most significant advantage biomass fuels have over fossil fuels is that their thermal utilisation is almost CO_2 neutral, meaning that the CO_2 emitted during combustion is the equivalent of the CO_2 consumed during the lifetime of the biofuel. Gough et al (2002) stated that substituting coal in electricity production with 1 ton of dry biomass reduces carbon in CO_2 emissions by about 0.5 tons. Therefore a typical crop of 8 tons per hectare results in a C reduction of about 4 tons or 14 tons of CO_2 emissions. In addition, recently designed biomass combustion systems have been able to achieve emission levels of other gases that are comparable to fossil fuels systems which previously had not been feasible (Biedermann & Obernberger, 2005).

1.2.2 Grain Drying

Whisky Industry

This whisky industry market is seen as hugely important to the Scottish economy, as Scotch Whisky is one of the top five export earners for the UK and contributes a massive £800 million in taxes annually to the UK[1]. Scotland has a significant part of that total UK market for malting barley which is around 1.7 million tonnes. 500,000 tonnes of malting barley is required for Scotch Whisky distilling, but the total annual requirement for malting barley in Scotland is around 650,000 tonnes. In the EU, the annual requirement is in the order of 8 to 9 million tonnes, and the total usage globally, is approximately 23 million tonnes.

The qualities needed in the malting barley used in the whisky industry, is low N (i.e. protein) content, high starch content, good grain size and very high germination qualities.

Drying the Grain

The main type of barley grown is the spring variety and it is harvested from halfway through July till the end of second week of August. After harvesting the grain is cleaned, dried and stored. The drying of the grain generally only occurs for two months of the year, August and September. There are a number of reasons[2] for drying grain, and they are as follows:

- Lowering the moisture content is necessary to prevent grain spoilage, which is primarily caused by mould and insect infestation
- Drying reduces the dependency on weather conditions for harvest and reduces the number of harvest-related equipment and labour required due to extending harvest time
- Drying increases the storage time of the grain for up to a year and prevents early germination

Drying reduces the amount of water contained in the crop after harvest to an acceptable level for marketing, storage, or processing. According to Maier & Bakker-Arkema (2002), the energy required to evaporate a unit mass of moisture in a high capacity grain dryer (i.e. the specific energy efficiency) ranges from 3.5 MJ to 7.0 MJ per kg of water, depending on the dryer design and the ambient conditions. Grain temperature and moisture content are critical in maintaining quality.

Grain driers used on sites such as East of Scotland Farmers Ltd (EOSF) and Highland Grain Ltd each have their own grain cleaning systems that operate throughout the drying process.

---

[1] http://www.highlandgrain.co.uk/

[2] http://www.ext.nodak.edu/extpubs/plantsci/smgrains/ae701-1.htm#Advantages

EAST OF SCOTLAND FARMERS LTD (EOSF)

EOSF owns a site in Coupar Angus with five grain driers and storage for around 40,000 tonnes of grain. EOSF is a cooperative system that allows farmer members to move grain off the farm quickly once it is cut. EOSF dries, conditions and stores grain, so that it can be delivered to customers over the course of the following year.

HIGHLAND GRAIN LTD

Highland Grain Ltd is the co-operative grain marketing group based at Tore outside Inverness and has three grain driers. Last year it processed around 30,000 tonnes with malting barley as 95% of the total and had an annual turnover of £3.5M. Highland Grain's target market is the Scotch Whisky industry.

Figure 1: Highland Grain Ltd, storage and drying facility

Grain Driers

On arrival the grain has about 20% moisture content and after drying the moisture content is reduced to 11.4 % for malting barely and sometimes less for feed grain. Therefore malting barley needs to be dried at a temperature of 60°C, and feed grain is dried at temperature of about 100°C.

The driers used at Highland grain are Cimbria driers and furnaces. Each drier has a 1- 2MW Weishaupt burner, which is a widely used brand of German burner. The burners are either fuelled by diesel or gas oil, and operate on a direct heating principle. The flue gas is conducted through the dryer and there is no loss in the chimney. The direct heating system ensures a clean and energy saving drying of a high capacity and is therefore often used in the drying of cereals[1]. The hot air furnace has an air mixing system which gives a homogenous drying air temperature. Each burner and drier has a control system that can monitor and dictate that amount of heat, grain and air in the system.

At Highland Grain, their 3 burners use about 79 gallons of diesel oil an hour during peak season, this equates to about power output of about 3.54 MW an hour. Highland Grain estimated that a new diesel oil burner would cost about £1500 for a modular system and about £6000 for a burner with full control system.

1.2.3 Grain-dust

Burning Grain

Hytönen (2000) discusses how in recent years, interest in using grains like oat and barley for heating has grown in Finland due to the high price of oil and low price of oats.

'*While the price of grain is low and the cost of the fuel needed to dry it is high, it makes sense to investigate using grain as a fuel, particularly in countries like Scotland, which produces 300,000 surplus tonnes of barley a year*,' says Hamish Walls of the Scottish Agricultural Organisation Society (SAOS).

Burners on a small scale have been developed so that they can burn grain. The current price of oil has consequently meant it is more economic to burn grain than sell it for food. However this raises ethical issues over whether a source of food should be burnt to provide energy when people in developing countries are starving.

Grain-dust has not yet been examined as a fuel source at this point in time; however the use of cereal grain as a possible boiler fuel has been discussed for a number of years largely due to two specific issues:

i.) Excess feed grain on the market
ii.) Heating value of grain

The first issue arises due to the need for an outlet for damaged grain when tighter EU legislation on feed grain quality comes into force (Rice, 2005). Recently increased oil prices and falling feed grain prices has also given weight to discussions. The second issue that has generated discussion is that all cereal grains have similar heat values; although oats have the highest value due their high oil content. At 15% moisture content, cereal grains

---

[1] http://www.cimbria.com/grp_download.asp

have heat values similar to wood chips. However the energy density of grain is about three times higher than wood chips, which therefore reduces storage (Rice, 2005).

Based on data retrieved from the DTi (2006) during their fact-finding mission to Denmark on the possibilities for burning grain, some simple analysis on the benefits of using grain-dust as a fuel can be summed up in the following table.

Fuel	Net heat value (MJ/kg) on DM basis	At normal moisture	Bulk density (kg/m^3)	Energy density (GJ/m^3)	Current bulk delivered cost	Quantity required to provide 35.7 MJ	Cost to provide 35.7 MJ (ie = 1 litre oil)	Cost per kWh
Wheat (grain)	17	14.1 (15% MC)	750	10.6	£75/t	2.53 kg	19.0 p	1.92 p
Barley (grain)	17.5	14.5 (15% MC)	690	10.0	£70/t	2.46 kg	17.2 p	1.73 p
Barley (screenings)	17.5	15.1 (12% MC)	620	9.4	£65/t	2.36 kg	15.3 p	1.54 p
Wood pellets	18.4	16.4 (10% MC)	650	10.7	£136/t	2.18 kg	29.6 p	2.98 p
Oil	42	42 (0% MC)	850	35.7	34 p/litre	1 litre	34.5 p	3.48 p

Table 1: Comparative values and costs (DTi, 2006)

Origins of Grain-dust

Grain driers used on sites such as East of Scotland Farmers Ltd (EOSF) and Highland Grain Ltd each have their own grain cleaning systems that operate throughout the drying process.

Throughout the drying process cyclo-fans capture about 80% of the grain-dust and then it is placed into storage. Eventually the waste usually goes to landfill sites and this can cost of up to £10,000 a year, taking into account landfill tax and transport.

EOSF produces about 200 – 250 tonnes of grain-dust a year, and Highland Grain produces about 150 – 200 tonnes. In addition, Highland Grain estimated that 5% of its yearly turnover is ‘seconds’. Seconds is the term that refers to barley product that does not meet the quality standard required such as screenings, husk, and small grain. At Highland Grain, ‘seconds’ equate to about 1500 tonnes in a year. If grain-dust proved to be feasible option seconds could be used in milled form for extra fuel.

The composition of the grain-dust that is intended for burning is essentially chaff, screenings and crushed grain. Therefore the assumption is that its values for heat and energy density will not be as high as barley grain, conversely the values will not be as low as the values for the values for barley straw. It is supposed that the values will be somewhere in the middle of the values for grain and the values for straw.

1.2.4 Dust Burners

Wood dust burners have existed for a number of years, however no commercial models are specifically marketed as grain-dust burners. Conversely grain-burning boilers are on the market, especially in Denmark and Austria, but are not as advanced as those for wood chips or pellets.

Most wood burners are likely to be suitable for other biomass fuels without substantial changes. A more complex combustion-air distribution system is needed for grain than for wood chips, as the grain packs more tightly and restricts air movement. However this is unlikely to be the case for grain-dust

Studies have shown that the higher Cl content of grain has led to corrosion problems in the past, although this can be largely overcome by the use of corrosion-resistant materials.

There are a number of associated problems with grain combustion such as more ash, more complex combustion control and more emissions. Therefore a grain-burning system will cost considerably more than a similar burner for oil or gas and this has to be taken in to account. However considering the grain-dust is surplus waste compared to oil and its rising cost; it is likely that initial outlays would be regained over the long term.

Fuel	Net Calorific value [MJ/kg]		Bulk density [kg/m3]	Energy density [GJ/m3]
	On DM basis	normal moisture		
Wheat (grain)	17	14.1 (15% m.c.)	750	10.6 (15% m.c.)
Barley (grain)	17.5	14.5 (15% m.c.)	690	10.0 (15% m.c.)
Oats (grain)	18	14.9 (15 % m.c.)	560	8.3 (15% m.c.)
Willow chips	18.4	13.2 (25% m.c.)	195	2.6 (25% m.c.)
Oil	42	42 (0% m.c)	850	35.7

Table 2: Energy values (BIOBIB and DTi)

1.2.5 Potential Issues

The main disadvantage of utilising biofuels is ash-related problems which affect particulate emissions and cause internal plant problems such as slagging, deposit formation and corrosion (Biedermann & Obernberger, 2005). Currently the ash forming properties of straw, which are largely due to K and Cl content, are a major obstacle for an efficient utilisation of straw as a fuel for power production (Sander, 1997). As a large proportion of the grain-dust is straw and chaff, this issue is particularly relevant for the feasibility and progress of grain-dust burners.

Fouling and Slagging

One of the problems with burning grain is its high K content that leads to ash melting at a lower temperature. Grain ash melts at about 700ºC (wheat) to 1000ºC (oats) compared to about 1300ºC for willow chips (Rice, 2005). This often leads to slag formation in the combustion chamber, which is the formation of lumps of congealed ash that may block the air supply and impede ash removal.

The high K and Si content of barley (3%) compared to that of saw-log wood (0.5%) increases its ash content. Therefore ash disposal is a bigger problem. In addition, dust emissions are also increased, so the installation of flue-gas cleaning equipment is usually recommended (Rice, 2005).

Emissions

Carbon monoxide emissions are lower for grain than wood; however the high N content in the grain leads to increased NO_x-emissions compared to wood. Reduction of these emissions by selecting grain with low protein content is unlikely to be practical. Therefore installation of NO_x of flue-gas cleaning equipment is necessary to deal with these emissions (Rice 2005).

2) Composition and Combustion

2.1 Composition of Biomass

Jenkins et al (1998) discuss how photosynthesis results in the production of structural and non-structural carbohydrates which make up the plant tissues. The components of biomass include cellulose, hemicelluloses, lignin, lipids, proteins, simple sugars, starches, water, hydrocarbons, ash, and other compounds. The concentrations of each component vary depending on species, type of plant tissue, stage of growth, and growing conditions.

According to Jenkins et al (1998) biomass fuels can be divided quite generally into four primary classes:

a) Wood & woody materials
b) Herbaceous and other annual growth materials such as straws, grasses, leaves,
c) Agricultural by-products & residues including shells, hulls, pits, & animal manure
d) Refuse-derived fuels & waste or non-recyclable papers, often mixed with plastics

Hytönen (2000) discusses how Agrofuels are classified according to FAO (Food and Agriculture Organization of the United Nations) into fuel crops, agricultural by-products (straw, stalks), animal by-products (dung and other excreta) and agro-industrial by-products. Therefore grain-dust that results from drying barley is referred to as an agricultural by-product.

The composition of biofuels is complex; the main components include six major elements C, H, O, N, S, Cl and at least 8 other elements Si, Al, Ca, K, Mg, Na, P, and Fe.

The principal constituent of biomass is C, making up from 30 to 60% weight of dry matter depending on ash content (Jenkins et al, 1998).Usually 30 to 40% weight of the dry matter in biofuels is Oxygen. The third major constituent is H, comprising typically 5 to 6% of the dry matter. N, S, and Cl are usually less than 1% of the dry matter, but it may exceed this value in different biofuels (Paulrud, 2004).

The dominant ash forming components in biofuels are alkali metals, alkaline earth metals, and Si. Compared to wood, straw is an ash-rich fuel and contains higher levels of Si and K, and contains a higher content of Cl, N, and S (Paulrud, 2004). Research shows that biofuels have much lower S content than coal, however the N content in straw is comparable to coal, but is lower in wood (Sander, 1997).

2.1.1 Fuel Quality

According to Paulrud (2004), the term ‘fuel quality’ defines the chemical and physical characteristics of a fuel. Chemical characteristics depend on raw material, growing conditions, and agricultural management. Chemical characteristics include:

- Moisture content
- Ash content
- Concentrations of inorganic elements
- Ash forming elements

Physical characteristics describe parameters of the fuel that are affected by the type of processing the biomass has undergone. Therefore physical characteristic include:

- Particle size
- Particle shape
- Bulk density
- Mechanical

In the case of grain-dust, it is necessary to determine the chemical and physical properties of barley grain and straw in order to design an effective and efficient combustion system.

2.2 Chemical Make-up of Barley

Most common biofuels such as bark, straw and cereals contain quite similar concentrations of C, H and O but show significant differences in the concentrations of the main ash forming constituents (Si, Ca, Mg, K, Na, P, S, CI, AI, Fe, Mn), and of heavy metals (Cu, Zn, Co, Mo, As, Ni, Cr, Pb, Cd, V, Hg) according to Obernberger (1997). These inorganic elements influence the combustion process in a variety of ways:

- by forming gaseous and solid emissions
- by significantly influencing the ash melting behaviour
- by fouling and by corroding furnace walls (Obernberger, 1997)

Therefore in order to design the combustion plant and control system suitable for a particular biofuel, the amounts of inorganic elements and effects they cause during combustion must be known (Obernberger, 1997).

2.2.1 Elements Influencing Ash Formation

Biedermann et al (1997), state that the concentrations of the major ash-forming elements in biofuels directly influence the amount of ash that will be produced. Therefore straw and cereals are ash-rich biofuels, compared to wood which is an ash-poor biofuel. The amount of ash produced is relevant for the design of ash manipulation and ash storage systems in addition to the possibilities for ash recycling (Biedermann et al, 1997).

The main ash forming elements in biofuels are Si, Ca, K, Mg and P. Si combined with K can lead to the formation of low melting silicates in fly-ash particles (Biedermann et al, 1997). As K is relatively volatile, it forms chlorides, hydroxides and sulphates, all of which play an important role in the corrosion (Biedermann et al, 1997). Ca is less volatile than K but also forms chlorides and sulphates (Biedermann et al, 1997).

Ca and Mg usually increase the ash melting point while K and Na decrease it (Biedermann & Obernberger, 2005). Chlorides and low melting alkali- and alumosilicates may also significantly decrease the ash melting point (Miles, 1996). A low ash melting point leads to sintering or slag formation in the combustion chamber and this subsequently leads to reduced plant efficiency and lifetime.

Straw, cereal, grass and grain-ashes contain low concentrations of Ca and high concentrations of Si and K according to Biedermann & Obernberger (2005) and therefore start to sinter and melt at significantly lower temperatures than wood fuels. Van loo & Koppejan (2002) therefore state that Si, K and Ca concentrations must be considered when selecting the appropriate combustion and temperature control technology.

Oxides and to a smaller extent carbonates are the major compounds formed from Ca and Mg during biomass combustion (Biedermann et al, 1997). According to Biedermann et al (1997), Ca, Mg, K and P are also plant nutrients and soil improvement agents, and thus provide opportunities for the utilisation of biomass ashes in forests or on agricultural fields.

2.2.2 Elements Influencing Emissions and Corrosion

Straw and cereals contain significantly higher amounts of N, S and Cl compared to woody biofuels and therefore it is necessary to adjust the combustion and flue gas cleaning technology accordingly (Biedermann et al, 1997). Concentrations of N, S and Cl in different biofuels are of major importance because they cause gaseous emissions such as NO_x, SO_x and HCl. The parameters that affect the formation of these emissions are excess

O_2 and CO concentration in the flue gas, furnace temperature and furnace geometry, as well as the dust precipitation systems. However, high concentrations of N, S and Cl in the biofuel have the most influence on increased gaseous emission levels (Biedermann et al, 1997).

N is almost completely converted to the gaseous phase (N_2, NO_x) during combustion (Biedermann et al, 1997).

The main influences of Cl are:

- Corrosive effects on metal surfaces in furnaces and boilers
- Hydrochloric acid in gaseous form
- Particulate (KCl, NaCI, ZnCI2) emissions

When biofuels have Cl concentrations above 0.1 % wt (db), related corrosion issues are to be expected to be a problem and therefore are relevant for straw, cereals and grasses. Measures against corrosion include automatic heat exchanger cleaning systems, coating of the boiler tubes, appropriate material selection as well as optimised combustion and process control technologies according to Biedermann & Obernberger (2005).

Biedermann & Obernberger (2005) explain how the S contained in the solid biofuel forms mainly gaseous SO_2 and alkali sulphates. In addition to SO_2 emissions, S has an important role in corrosion processes. Biedermann & Obernberger (2005) discuss how high SO_2 concentrations in the flue gas causes sulphation of alkali and earth-alkali chlorides consequently leading to the release of Cl with decreasing flue gas temperatures. The released Cl can cause corrosion through $FeCl_2$ or $ZnCl_2$ formation at the metal surfaces via ash particles precipitated on the surface of heat exchanger (Biedermann & Obernberger, 2005)

Investigations have shown that the ash of straw (wheat) or cereal after combustion contained 40 to 55% S, compared to 40 to70% in the case of wood chip combustion. Alkali and earth-alkali metals (especially Ca) concentrations in the fuel affect the efficiency of S-fixation in the ash (Biedermann & Obernberger, 2005).

As S, Cl and N all play a major part in emission and corrosion lower concentrations of S, Cl and N in biofuels are better for the combustion (Biedermann et al, 1997).

2.3 Current Chemical Data

At this time it was possible to find sparse analysis on various biofuels in the literature, however most information was mostly incomplete and in some cases contradictory. The main aim of the data search was to find suitable sources of data for the chemical and physical properties of barley straw and grain separately in order to ascertain the potential properties of grain dust.

The sources selected for data comparison were:

- BIOBIB - A Database for Biofuels
- Jiang et al (2005)- Analysis of Grain Screenings
- CEN/TS 14961 – Combined data for ‘wheat, barley and rye’ straw and grain
- Obernberger et al (2004) – Data the same as the CEN/TS data

These sources were selected for their ‘completeness’ of data in the required areas, however exact data for some properties such as the silicon content of grain compared to straw was hard to find. Data relating to the exact values of barley grain was not found over the course of the project, only scattered values or ranges of value were obtained for barley grain.

2.3.1 BIOBIB - A Database for Biofuels

A database for Biofuels was begun in 1992, due to the increased utilisation of biofuels for heat and power production in the European Union[1]. BIOBIB was created to bring together the most relevant data for thermal utilisation of biofuels analysed by standard analytical methods. BIOBIB covers fuels such as woody biomass, cereals and biomass- waste-assortments such as waste wood, particle boards, husks and shells from different plants and industrial residues.

BIOBIB includes data of the ultimate analysis of the elements, the proximate analysis, the analysis of the minor and trace elements, and data about the melting behaviour of the ashes.

Main fields	Description
ash	analysis of the ash content
ultimate analysis	analysis of C, H, N, S, Cl
calorific value	analysis of the gross and net calorific value
proximate analysis	analysis of Si, Fe, Al, Ca, Mg, Na, K, Ti, CO_2, SO_3 and Cl
ash- thermal behaviour	analysis using DIN 51 730 in oxygen atmosphere
ash- heavy metals	analysis of Pb, Cd, Cu, Hg, Mn, Cr
other analysis	analysis of Mg, Ca, Al, Si, P, Fe, Pb, Cd, Cu, and others

Table 3: Classification of the properties represented in BIOBIB

---

[1] http://www.vt.tuwien.ac.at/Biobib/biobib.html

Different data was analysed by different laboratories using different analytical methods and so the data was compared and checked by a various analysis.

The data used from the biofuels database is data for three varieties of barley straw; however values for barley grain were unavailable. See complete BIOBIB data in Appendices 10.2

2.3.2 Jiang et al (2005): Analysis of Grain Screenings

The analysis was carried out by Jiang et al (2005) on grain screenings, an agricultural residue, which is a by-product of feed and food production. The X-ray photoelectron spectroscopy provides useful information for biomass combustion

Fuel Analysis of grain screenings (ash free basis)	
Element	**% by weight**
C	41.00
H	5.60
O	31.61
N	1.83
S	0.22
Moisture	11.47
As received	
Ash	8.27
Lower heating value	16.397 MJ/kg

Ash composition of grain screenings (percent of ash basis)	
Compound	**Mass %**
SiO_2	34.4
Al_2O_3	2.2
Fe_2O_3	2.6
CaO	15.8
MgO	3.9
Na_2O	1.9
K_2O	19.2
SO_3	5.1
P_2O_5	11.6
Cl	2.8

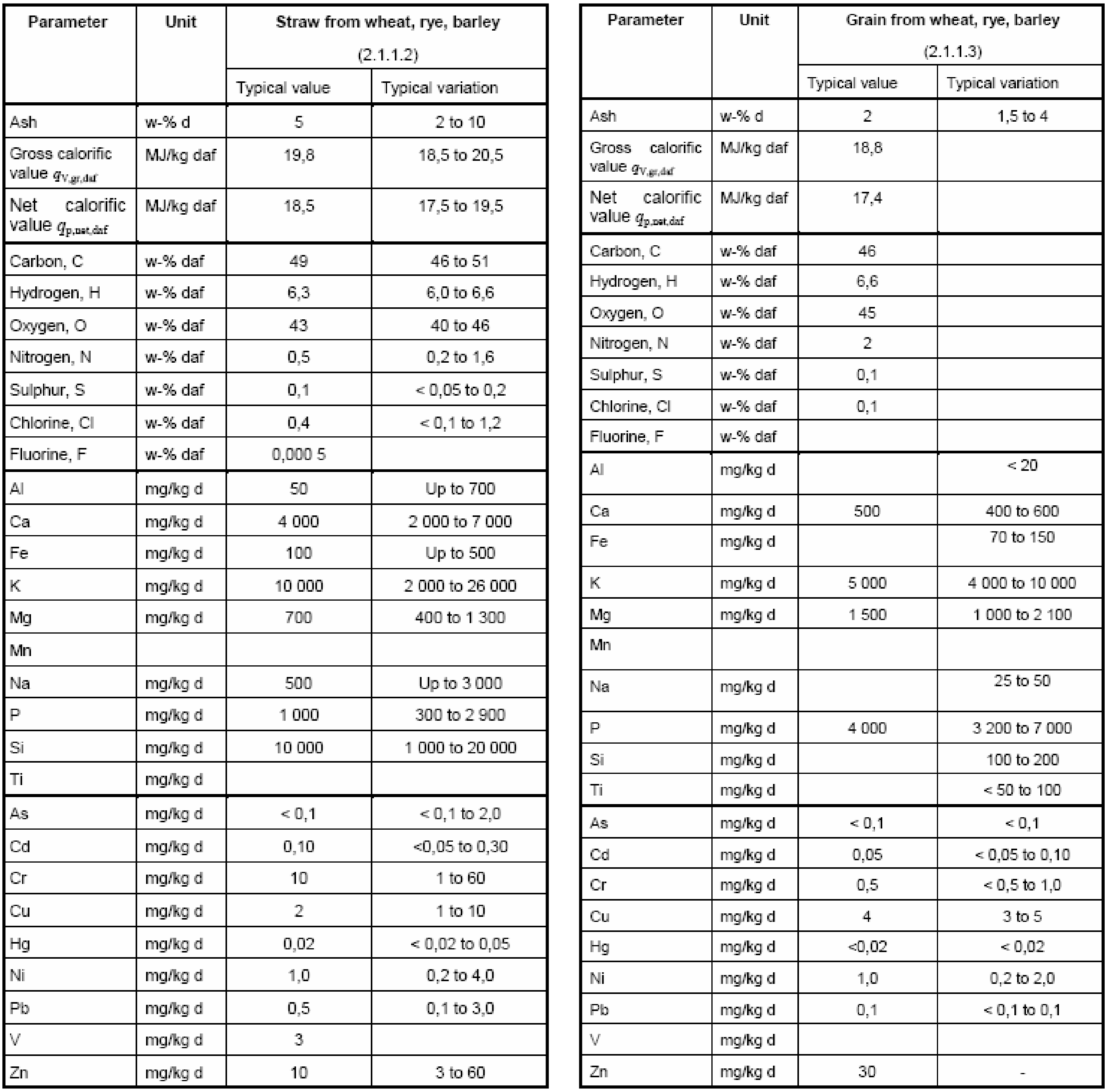
Table 4: Analysis on grain screenings (Jiang et al, 2005)

The data obtained by Jiang et al (2005) is useful as it takes into grain screenings rather than just grain and therefore is likely to be a combination of both straw and grain. However it is not specific to barley grain and this might cause some deviation in the results when compared with actual barley screenings.

2.3.3 CEN/TS 14961

This data was obtained from Technical Specification, CEN/TS 14961, "Fuel Specifications and Classes", published by European Standards.

It was found in Annex C, ‘Typical values of solid biomass fuels’, and contained information for ‘wheat, barley and rye’ straw and grain. The data was obtained by CEN from a combination of mainly Swedish, Finnish, Danish, Dutch and German research. The values only aim to describe properties that can be expected in Europe in general.



Parameter	Unit	Straw from wheat, rye, barley (2.1.1.2)	
		Typical value	Typical variation
Ash	w-% d	5	2 to 10
Gross calorific value $q_{V,gr,daf}$	MJ/kg daf	19,8	18,5 to 20,5
Net calorific value $q_{p,net,daf}$	MJ/kg daf	18,5	17,5 to 19,5
Carbon, C	w-% daf	49	46 to 51
Hydrogen, H	w-% daf	6,3	6,0 to 6,6
Oxygen, O	w-% daf	43	40 to 46
Nitrogen, N	w-% daf	0,5	0,2 to 1,6
Sulphur, S	w-% daf	0,1	< 0,05 to 0,2
Chlorine, Cl	w-% daf	0,4	< 0,1 to 1,2
Fluorine, F	w-% daf	0,000 5	
Al	mg/kg d	50	Up to 700
Ca	mg/kg d	4 000	2 000 to 7 000
Fe	mg/kg d	100	Up to 500
K	mg/kg d	10 000	2 000 to 26 000
Mg	mg/kg d	700	400 to 1 300
Mn			
Na	mg/kg d	500	Up to 3 000
P	mg/kg d	1 000	300 to 2 900
Si	mg/kg d	10 000	1 000 to 20 000
Ti	mg/kg d		
As	mg/kg d	< 0,1	< 0,1 to 2,0
Cd	mg/kg d	0,10	<0,05 to 0,30
Cr	mg/kg d	10	1 to 60
Cu	mg/kg d	2	1 to 10
Hg	mg/kg d	0,02	< 0,02 to 0,05
Ni	mg/kg d	1,0	0,2 to 4,0
Pb	mg/kg d	0,5	0,1 to 3,0
V	mg/kg d	3	
Zn	mg/kg d	10	3 to 60

Parameter	Unit	Grain from wheat, rye, barley (2.1.1.3)	
		Typical value	Typical variation
Ash	w-% d	2	1,5 to 4
Gross calorific value $q_{V,gr,daf}$	MJ/kg daf	18,8	
Net calorific value $q_{p,net,daf}$	MJ/kg daf	17,4	
Carbon, C	w-% daf	46	
Hydrogen, H	w-% daf	6,6	
Oxygen, O	w-% daf	45	
Nitrogen, N	w-% daf	2	
Sulphur, S	w-% daf	0,1	
Chlorine, Cl	w-% daf	0,1	
Fluorine, F	w-% daf		
Al	mg/kg d		< 20
Ca	mg/kg d	500	400 to 600
Fe	mg/kg d		70 to 150
K	mg/kg d	5 000	4 000 to 10 000
Mg	mg/kg d	1 500	1 000 to 2 100
Mn			
Na	mg/kg d		25 to 50
P	mg/kg d	4 000	3 200 to 7 000
Si	mg/kg d		100 to 200
Ti	mg/kg d		< 50 to 100
As	mg/kg d	< 0,1	< 0,1
Cd	mg/kg d	0,05	< 0,05 to 0,10
Cr	mg/kg d	0,5	< 0,5 to 1,0
Cu	mg/kg d	4	3 to 5
Hg	mg/kg d	<0,02	< 0,02
Ni	mg/kg d	1,0	0,2 to 2,0
Pb	mg/kg d	0,1	< 0,1 to 0,1
V	mg/kg d		
Zn	mg/kg d	30	-

Table 5: Values for 'wheat, barley and rye' straw and grain (CEN/TS 14961, Annex C)

2.3.4 Obernberger et al (2004)

Obernberger et al (2004) listed various data in numerous papers, some of which is detailed in Section 5.6, Table 14, and bears a noticeable resemblance to the data listed by the CEN/TS14961. The level of collaboration between the two parties is unknown.

2.4 Chemistry of Combustion

2.4.1 Complete combustion

Boyles (1984) discusses how the simplest method of extracting useful energy from dry biomass it to burn it using air as the oxidant. The chemistry of complete oxidation of material containing mainly C, O and H is as follows:

$$C_xH_YO_Z(biomass)+\left[x+\frac{y}{4}-\frac{z}{2}\right]O_2 \quad \rightarrow \quad xCO_2+\frac{y}{2}H_2O$$

- where x, y and z represent the mean elemental composition of the biomass

If combustion is incomplete due to insufficient O_2 then C, CO, hydrocarbons and other gases are formed and the heat of the reaction is reduced. Other elements present in the biomass such as N are converted to gaseous products and ash.

The thermodynamic heat yield of the combustions reactions is not reduced by the presence of moisture in the biomass. However the efficiency is reduced due to the added requirement of heating up the water contained and evaporating it at combustion temperatures, in addition the flame temperature and combustion rate are also reduced. A water moisture content of more that 30 % prevents direct burning and therefore drying is necessary or alternatively a supplementary fuel can be added. Boyles (1984) states that direct combustion in a suitable device can be one of the most efficient methods of utilising the energy potential from biomass, and thermal efficiencies of up to 85% can be achieved.

2.4.2 Combustion of Biofuels

Jenkins et al (1998) state that combustion of biofuels is a complex phenomenon involving simultaneous coupled heat and mass transfer with chemical reaction and fluid flow. To predict combustion behaviour for design and control purposes requires knowledge of fuel properties and the manner in which these properties influence the outcome of the combustion process. Jenkins et al (1998) provide a global reaction for the combustion of a biomass fuel in air in the following form, where the first reactant compound is a biomass fuel:

$$
\begin{aligned}
&\mathrm{C}_{x1}\mathrm{H}_{x2}\mathrm{O}_{x3}\mathrm{N}_{x4}\mathrm{S}_{x5}\mathrm{Cl}_{x6}\mathrm{Si}_{x7}\mathrm{K}_{x8}\mathrm{Ca}_{x9}\mathrm{Mg}_{x10}\mathrm{Na}_{x11}\mathrm{P}_{x12}\mathrm{Fe}_{x13}\mathrm{Al}_{x14}\mathrm{Ti}_{x15} + n_1\mathrm{H_2O} \\
&\quad + n_2(1+e)(\mathrm{O_2} + 3.76\mathrm{N_2}) = n_3\mathrm{CO_2} + n_4\mathrm{H_2O} + n_5\mathrm{O_2} + n_6\mathrm{N_2} + n_7\mathrm{CO} \\
&\qquad\qquad + n_8\mathrm{CH_4} + n_9\mathrm{NO} + n_{10}\mathrm{NO_2} + n_{11}\mathrm{SO_2} \\
&\qquad\qquad + n_{12}\mathrm{HCl} + n_{13}\mathrm{KCl} + n_{14}\mathrm{K_2SO_4} + n_{15}\mathrm{C} + \ldots
\end{aligned}
$$

Using rice straw (Jenkins et al, 1998) as an example, the values for x in the equation are as follows:

C	H	O	N	S	Cl	Si	K	Ca	Mg	Na	P	Fe	Al	Ti
x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}
3.2072	5.1973	2.8148	0.0625	0.0057	0.1000	0.5000	0.5000	0.0592	0.0135	0.0079	0.0086	0.0029	0.0073	0.0004

The empirical formula for the fuel is incomplete as there are than 15 elements, some of which are important to the issue of biomass combustion, for example heavy metals, which have a strong influence on ash disposal (Jenkins et al, 1998).

The second reactant term expresses the moisture in the fuel, which varies within a certain range but it is important to note that if too much moisture is present, the fuel will not spontaneously react.

The third term is a simplification and represents air by the simple binary mixture of O and N in the volume ratio of 21% to 79%.

According to Jenkins et al (1998) the product side of the reaction is complex. The main products appear first, however there are a number of additional products. These products include:

- Atmospheric pollutants such as carbon monoxide (CO), hydrocarbons (HC), oxides of N and S
- Reactions among inorganic species that lead to fouling and slagging, such as the alkali-chlorides, sulphates, carbonates and silicates

The above products are important issues for the operation of a commercial biomass combustion system (Jenkins et al, 1998).

Jenkins et al, 1998 state that the detailed chemistry for above global reaction is far from understood, and therefore making generalisations and engineering recommendations concerning the design of biomass combustion systems is made difficult by the variable composition of biomass. The complex structure of biomass has a significant influence on its combustion behaviour.

2.4.3 The Energy Value of Biomass

According to Jenkins et al (1998), the standard measure of the energy content of a fuel is its heating value, sometimes called the *calorific value* or heat of combustion. There are multiple values for the heating value, which depend on whether the value measures the enthalpy of combustion, the internal energy of combustion, and whether the product water is accounted for in the vapour phase or the condensed (liquid) phase.

According to Jenkins et al (1998), the enthalpy of combustion is usually determined at constant pressure, and so includes the work flow. With water in the vapour phase, the lower heating value at constant pressure measures the enthalpy change due to combustion and is also referred to as the Net Calorific Value (NCV). The enthalpy change of combustion is the higher heating value at constant pressure with water condensed and is called the Gross Calorific Value (GCV).

However if the combustion is carried out at constant volume, the higher heating value at constant volume is the internal energy change due to combustion with water in the condensed state, while the lower heating value at constant volume measures the internal energy change with product water in the vapour phase. Due to the inconsistencies of measurement method, values of thermal efficiency are often difficult to interpret. There is a need for thermal efficiency determinations to adhere to the same standards for direct comparisons (Jenkins et al, 1998).

Moisture in the fuel reduces the heating value compared to a dry weight determination and is therefore a limiting factor in biomass combustion. This is because the combustion reaction is an exothermic reaction unlike the evaporation of water which is strongly endothermic. The moisture content (mass of water per mass of moist fuel) limit for self-supporting combustion for most biomass fuels is around 65%. Insufficient energy is liberated by combustion to satisfy evaporation and product heating above 65% moisture content. When burning biomass in excess of 50 to 55% moisture, most combustors require a supplemental fuel, such as natural gas. In addition CO and other products of incomplete combustion may be emitted in greater quantities depending on the design of the combustor (Jenkins et al, 1998).

According to Jenkins et al (1998), heating values are related to carbon concentration, for each 1% increase in C, the heating value is increased by approximately 0.39MJ kg^{-1}. In addition, the heating value relates to the amount of O required for complete combustion, with 14,022 J released for each gram of O consumed The heating value of biomass can be partially correlated with ash concentration, each 1% increase in ash translates roughly into a decrease of 0.2 MJ kg^{-1} (Jenkins et al, 1998).

Jenkins et al (1998) discuss how the heating value of a fuel relates to the 'quality' of the fuel as an energy source. The rate of combustion is also important in the design of combustion systems in addition to the energy released by combustion (Jenkins et al, 1998)

3) Comparable Technology

3.1 Extent of Current Technology

Wood dust burners have existed for a number of years; however grain-dust burning is currently not a recognised technology. A number of manufacturers advertise biomass burners and biomass dust is included with the list of feed stocks for some models. However the extent to which this has been employed or tested is unclear, the conditions and technology necessary for burning grain-dust differ from burning wood dust, although there similarities. Some alternative technologies other than dust burners will be explored in this section In addition to straw biomass, which has been a biomass feedstock for a long time, is examined as it highly relevant, as grain-dust contains a large proportion of straw.

3.2 Straw Biomass

Currently straw is being examined and utilised as a biomass fuel. Much of the knowledge gained through the processing and combustion of straw can be used to identify issues and solve problems for ‘Grain-dust Burning’.

According to DTi (1999), ‘Energy from Biomass’ report, the main straw-producing crops are barley, wheat and oil-seed rape. Therefore conclusions and information can be drawn from the burning of straw derived from barley and then compared to the burning of barley grain.

In the paper entitled ‘Energy from Biomass, Volume 5: Straw, Poultry Litter and Energy Crops as Energy Sources’ produced by the DTi in 1999, the combustion and energy-utilisation of straw is discussed in some detail. The gross calorific value of straw at 15% moisture content is 14.8MJ/kg, which is approximately half the value of coal and one third of the value of oil (Silsoe College, 1985). The low density of straw compounds its low energy content, and therefore its ‘energy density’ is about one quarter of that of coal. Straw contains about 70% volatiles, therefore combustion involves the distillation of these volatiles which burn in a gas-phase to leave a mixture of char and ash. To burn the char, higher temperatures and large quantities of air are required. The ash produced is not comparable to coal ash. It has a low fusion temperature, and tends to melt at about 1050ºC although temperatures as low as 820ºC have been recorded. (Energy from Biomass, Vol. 5 1999)

Straw can be combusted in a variety of ways however it is valuable to note that according to the DTi (1999) 'Energy from Biomass' report, chopped straw readily lends itself to cyclone-type furnaces in which the straw is conveyed in the air stream, as these furnaces have long path lengths that allow very high combustion efficiency. The highly turbulent mixing of air and fuel that occurs in suspension firing systems produces the ideal conditions for complete combustions in the short time available. In addition, volumetric fuel feed rates are not restrictive due to the low residence times in the combustion chamber. A cyclone burner could be retrofitted to an existing drier in place of a conventional oil burner. (Energy from Biomass, Vol. 5 1999)

The DTi (1999) suggests that deep fluidised beds (see further discussion in RDF section) are potentially suited to straw utilisation; however shallow fluidised bed systems are less suitable. This is because most of the combustion takes place above the fluidised bed due to the high volatile content of straw and therefore supplementary fuel is needed to maintain bed operating temperatures.

3.2.1 Case Study

Straw Burning Through a Low-NO_x Axial Swirl Burner

In the DTi (1999) Energy from Biomass report, Babcock Energy Ltd carried out some tests for straw burning in a Babcock 12MW low-NO_x axial swirl burner in 1991. The details and results of the tests that are relevant to dust burning are as follows:

- Chopped straw screened at 12.5 mm was used
- Tests showed a need for a feeder capacity of 1000kg/hour to give the full burner load associated with stable flames
- The low-NO_x axial swirl burner proved prone to blockages at straw feed rates of 1000kg/hour
- A stable flame was obtained at approximately 50:50 straw: oil input
- Straw burned well with a long thin flame
- However the large particle size of the straw probably contributed to large quantities of burning material floated around the furnace, therefore reducing the size could alleviate the problem

Although oil support was necessary for the test, Babcock hypothesise that purpose designed feeding equipment instead of modified existing equipment could fire unsupported on straw or with a low level of support.

3.2.2 Economics of Straw Biofuel

According to FEC Consultants (1988), straw is a low-grade fuel compared to coal. It has a high volatile content (typically 65%) and a low calorific value (typically 15 MJ/kg). The ash content of straw is comparable to coal, but the S content is much lower, 40% of that for coal for an equivalent plant output. However the low bulk density and calorific value of straw means that 27 times the volume of chopped straw is required to match the energy content of coal. This has implications for fuel storage, handling and combustion system design.

The magnitude of the handling-problems diminishes with straw length as loose straw is difficult to handle, and serious bridging problems occur, hoppers and compaction increase these problems. Straw ignition and complete combustion occurs at lower temperatures compared with coal and also takes place more rapidly. The high volatile content of straw dictates that most of the combustion takes place in the gas phase; therefore the correct provision of secondary combustion air is essential for efficient combustion (FEC Consultants, 1988).

Straw can be economically attractive as an alternative to more conventional fuels, not only on the farm but also in local industrial installations. The relative economics are greatly affected by four factors:

- Price of the alternative fuel; coal, oil, gas
- The delivered price of straw, determined by haulage and storage
- The annual load factor of the plant
- Investment capital required to convert the system to straw firing

FEC Consultants, 1988 discuss how each potential site needs to be individually evaluated. Existing, purpose-designed automatic straw handling/preparation plants are costly, and thus negatively affect the economics of straw firing. Therefore a simplified approach to straw handling is likely to reduce capital costs.

3.2.3 Straw Ash Characteristics

According to Babcock Energy Ltd (1993), results with a cyclone burner, which successfully used chopped straw, showed that the development of straw as a fuel is a feasible option, given the right equipment and an appropriate economic environment. Therefore they characterised straw in more detail and examined the nature and behaviour of straw ash under industrial boiler conditions.

The test work was based on a number of different straw samples, which included barley and wheat straw. The samples were used for straw characterisation, straw ash characterisation, straw-coal co-firing experiments, sulphur retention studies and sodium and potassium volatilisation.

The results for the six straw samples indicated that straw is a typical high volatile, cellulose-based fuel with moderate moisture and low ash content. Results showed that moisture content ranged from 6.2 - 15.1% as received, reflecting differences in the original moisture contents of the straws. Volatile matter contents varied between 62- 72% as received, and between 79.5-82% on a dry, ash free basis. The S and N contents are low compared with most coals, and the Cl content (0.04-0.36%) is similar to that of British industrial coals. Although rape straw had lower ash content (3.5-4.0%) than cereal straw (5-6%), overall the fuel properties of the three types of straw were very similar (Babcock Energy Ltd, 1993).

Straw ash is significantly different to coal ash. Straw ashes are not alumino-silicate systems but instead consist of silica and simple inorganic salts, principally Ca and Mg carbonates and K - acid salts. Results showed that cereal straws are rich in amorphous silica and the potassium phosphates, with the carbonates present in lower concentrations. Cereal straws also have very different fusion properties, and that these reflect the major differences in their chemical and mineralogical composition. Cereal straw has a much lower ash fusion temperature compared to other biofuels. Therefore cereal straws are particularly prone to clinker and slag deposit formation, and this will present serious difficulties to boiler designers and operators (Babcock Energy Ltd, 1993).

3.2.4 Comparison of Straw and Grain

Sander (1997) evaluated the fuel quality relevant types of cereal energy crops and compared samples of grain and straw. Sander first examined and compared the content of Si, Ca, K and Cl in straw of the following species: winter barley, spring barley, and wheat. His results showed that cereal straw species are quite similar in composition. However there is a statistically significantly higher content of Si in wheat compared to other cereal species

When comparing straw and grain, grain was found to have a much lower content of ash, K, Ca, Si and Cl compared to straw, however it also had a significantly higher content of N. Therefore the tendency for slagging and fouling will be lower for whole crops than for straw, but that the emission of NO_x from combustion will be higher (Sander, 1997).

wt% on a dry basis	winter barley		spring barley		wheat	
	straw	grain	straw	grain	straw	grain
Ash	4.20	1.90	4.80	2.30	3.50	1.40
K	1.19	0.39	1.27	0.52	0.76	0.35
Ca	0.43	0.05	0.31	0.06	0.25	0.03
Si	0.29		0.64	-	0.65	0.01
Cl	0.67	-	0.69	0.15	0.36	0.07

Table 6: Comparison between composition of straw and grain (Sander, 1997)

3.3 RDF (Refuse Derived Fuel)

Parker and Roberts (1985) discuss how ‘Fluidised Bed Combustion’ of RDF (Refuse Derived Fuel) has been shown to be a very satisfactory method of recovering energy through the direct combustion of municipal waste. The process has high thermal efficiencies and is able to contain chloride and other micro pollutants by utilising a lime bed.

RDF technology has been focusing on:

- Improving the calorific value & combustion characteristic of waste
- Improving the handling characteristics of waste
- Reducing ash disposal and other residue problems

All the above areas are relevant to dust burning in as much as the need to:

- Improve the calorific value & combustion characteristic of dust so that as much energy is extracted in the most effective and efficient way
- Evaluate and assess the handling characteristics of dust and look at issues of storage, safety, transportation and incineration
- Minimise and address ash disposal and other residue problems

These factors have to be assessed in the light of production costs, energy output and input, waste disposal and fuel prices.

RDF can be classified in five basic categories: coarse, fluff, densified, powder and pulp. The types relevant to grain-dust burning are fluff & powder due to the nature of the grain-dust.

Parker and Roberts (1985) discuss how fluffy RDF is costly to transport and store due to its low bulk density and tendency to ferment and compact. In addition it is a fire hazard due to spontaneous combustion. These issues have lead to the development on ‘densified’ RDF, where the ‘fluff’ is extruded or pressed into cubes, pellets or briquettes to improve handling, transport and storage properties. However in order to achieve quality consistency in the pellets a drying stage tends to be necessary. Although this results in a higher calorific value product, and process energy input is required.

3.3.1 RDF Firing Processes

Parker and Roberts (1985) discuss how refuse incineration is a well established technique in Europe and the USA. However some of the problems being addressed at the time of writing were as follows:

- Reducing the quantity of flue gas and therefore plant and gas cleaning requirements by:
- Homogenisation of combustibles by crushing storing etc in order to equalise moisture
- Better distribution of the primary and secondary air in connection with the combustion chamber layout
- Improving air distribution in order to avoid hot spots and slag build-ups
- Flame regulation
- Improving the utilisation of slag by upgrading

As mentioned earlier ‘fluidised bed’ is a combustion technology whereby burning takes place in a bed kept turbulent by the passage of air, thus making the bed material behave like a liquid. This turbulence ensures a uniform temperature, high heat transfer rates and more complex combustion at low temperatures. The bed usually consists of sand; the sand’s heat capacity helps smooth out any changes in the calorific values of the feed stock. However the problems that have been encountered include

- Aluminium accumulation in the bed
- Good hard quality pellets are required for retention in shallow beds
- Relatively high fly ash particles requiring collection
- Slag formation if glass content of RDF is too high

Another type of incineration that has relevance is ‘Starved Air Combustion’. This technique differs from conventional incineration by restricting the amount of air necessary to support initial combustion. If necessary, auxiliary fuel, gas or oil is supplied to maintain the combustion process. The process is usually carried out in 2 chambers. The material oxides and volatiles are driven off in the primary process. In the second chamber volatiles are combusted.

Parker and Roberts (1985) state that tests on grit and dust emissions from the 2 stage combustion process results in much less carry-over in the gases compared to conventional large mechanical grate incinerators. This leads to less fouling and deposit build-up in the waste heat boilers and only simple cyclone collectors are needed to clean up exhaust gases.

In the context of burning dust, there is much that can be learnt can be learnt from tried and tested techniques such as burning RDF. In the event of a dust burner not being a financial or feasible alternative for grain waste burning comparable technologies such as fluidised beds might be a viable alternative.

3.4 Pellets and Powder

Biomass wastes such as sawdust, bark, and agro-residues such as barley screenings can be dried, milled, and compacted into fuel briquettes, fuel pellets, or finely milled to fuel powder. Paulrud (2004) discusses how the processing or upgrading is used to dry and standardise fuels by converting them into briquettes, pellets, and powder, and thus extends the use of biomass wastes as an energy source. Due to the varied particle size of the grain-dust, upgrading might be necessary for effective grain-dust burning. The benefits of upgrading can be listed as follows:

- easier to handle
- decreases transportation costs
- increases storage capacity
- improves combustion properties.

In Sweden, one of the countries at the forefront of biomass technology, upgraded biofuels (densified fuels and powder fuels) are mainly produced with raw material with low ash content such as sawdust and shavings from saw mills as opposed to crop residues. However, over the last five years, the use of upgraded fuels has increased so fast that other raw materials are generating increased interest (Paulrud, 2004).

An increased use of cereal crops as biofuels requires a study of potential problems associated with this new fuel. Undesired emissions and ash-forming elements resulting from higher concentrations of S, N, and Cl are likely to cause ash-related problems during combustion such as deposit formations in the boiler and convection area. The fuels used in Sweden in large-scale combustion plants are directly delivered as powder or delivered as pellets and milled before combustion.

In Sweden, according to Paulrud (2004), large-scale combustion plants mainly use powder burners, and the fuel is directly delivered as powder. The fuel however is often pelletised before being transported, then on arrival milled and combusted. This is because pellets have higher density than powder and are thus more economical to transport than powder and easier to store. However if the dust were produced on site, such as in a grain drying factory, pelletising is unlikely to be necessary.

3.4.1 Fuel Powder and Handling

Due to the risk for dust explosions, fuel powder is handled in closed systems from milling to storing in silos. In Sweden, the process for manufacturing wood powder is as follows:

- Coarse Milling - raw material is ground to a uniform particle size before drying
- Drying - raw material is dried to a moisture level of approximately 6%.using flue gas dryers or superheated steam dryers. Rotary-drum dryers using combustion gases as heating medium is the most common technique used in Sweden (Paulrud, 2004).
- Fine Milling - the material is finely milled in special mills; wood powder can be produced with a variety of different physical properties such as particle size distribution and particle shape.

During the fine milling process, the raw materials, type of mill and sieve affect particle size distribution and shape of the fuel powder. Paulrud (2004) states that Swedish producers mainly use impact mills in the milling process. Impact mills use discs, hammers, swing beaters, beater plates, or impeller plates to crush the material. Particle size, particle shape, and size distribution affect the handling properties of powders such as the tendency to bridge and flow in transport and storage systems. Furthermore, these parameters influence efficiency and emission levels when burning fuel powder.

There are a number of handling issues in regard to fuel powder that arise when a powder fuel has to be stored, removed from storage and transferred to some other destination (Paulrud (2004). For example, if the powder fuel is stored in a silo and a base aperture is opened, discharge of material may begin and then stop for no apparent reason before the silo is empty. Alternatively if the material is conveyed pneumatically through pipes, the material will not necessarily flow continuously even if the pipes are vertical (Paulrud (2004).

Upgrading might be necessary if it is not possible to burn the grain-dust due to the varying size of the particles contained within the samples provided. Chaff, husk, and straw are present in the grain-dust samples and this might need to be sieved or milled in order for the sample to be burnt effectively

4) Slag Formation & Emissions

4.1 Issues

In power plants, fuels with a high content of K and Cl cause a number of serious technical problems, such as increased slagging, fouling and corrosion of combustion units (Sander, 1997). A particular issue related to cereal product combustion is ash-formation. The content of ash-forming and gaseous pollutant-forming elements is higher in straw than in wood products. (Hytönen 2000, Sander 1997)

The DTi (2006) define slagging as the ash residue of fuel 'melts' in a boiler during the combustion process. Slagging can reduce the efficiency and can potentially cause major operational problems. Cereals such as barley are particularly affected due composition of chemicals in the grain; KCl and SiO_2 mix to form a chemical that melts at 700ºC.

Terms such as agglomeration, sintering, and melting are used in different ways in current literature but are generally used to refer to combustion deposits (Paulrud, 2004)

- Agglomeration is defined as the phenomenon where particles gather into clusters of larger size than the original particles (Zevenhoven-Onderwater, 2003).
- Sintering is defined as the phenomenon where loosely attached particles become more dense, forming a compact hard mass; different ways (Skrifvars, Backman & Hupa 1998):
- A melt that is formed in ash from biomass fuels can belong to either salts of alkali (mixtures of Na and K sulphates, chlorides and carbonates) and salts of alkaline earth metals (mixtures of Ca and Mg sulphates, chlorides and carbonates) or oxide/silicates systems.

The low melting point of cereal ash causes slag formation. The DTi (2006) discuss in their report entitled 'Grain – Fuel for Thought' how the chemistry of combustion of straw is very different to that of wood fuel, and therefore there are associated technical difficulties with burning of grain. They can be broadly categorised as follows:

- Ash
- Slag Formation
- Emissions

The above issues are discussed in the following sections.

4.2 Ash

4.2.1 Ash Formation

Ash is defined as the quantity of mineral matter which, after application of the described working methods, remains as incombustible residue of the tested substance by the ICC[1] .

In order to design the combustion plant and control system suitable for a particular biofuel, the amounts of inorganic elements contained in different biofuels, the reactions and effects they cause during combustion should be known (Obernberger et al, 1997). The major ash forming elements in biofuels are

- Al, Ca, Fe, K, Mg, Na, P, Si, S (Biedermann & Obernberger, 2005)

The DTi (2006) state how the high K and silica content of grains, and therefore grain-dust, contribute to a much higher ash residue after burning compared to that of wood biofuels. The ash content is as approximately as follows:

- Wood fuel 0.5% ash
- Cereal grains 3.5%-6% ash

Therefore any dust burning device should have an automated ash-removal system. Currently in Denmark, many of the installed grain burning systems include flue-gas cleaning systems to remove fly ash. This includes both cyclones and electrostatic precipitators (DTi, 2006).

Biedermann & Obernberger (2005) identify three different ash fractions that can normally be distinguished: bottom ash, cyclone fly ash and filter fly ash. See Fig. 2

- Bottom Ash: Ash fraction produced in the combustion chamber, often mixed with mineral impurities contained in the biomass fuel like sand, stones and earth. The mineral impurities can cause slag formation and sintered ash particles in the bottom ash, as the melting point of the ash is lowered
- Cyclone Fly-Ash: Fine, mainly inorganic, ash particles carried with the flue gas and precipitated in cyclones. Cyclone fly-ash consists of coarser fly ash particles compared to filter fly-ash
- Filter Fly-Ash: second and finer fly-ash fraction precipitated in electrostatic filters, fibrous filters or as condensation sludge in flue gas condensation units. In small

---

[1] http://www.icc.or.at/methods3.php

biomass combustion plants this ash fraction is emitted with the flue gas. This ash fraction consist mostly of aerosols, which are very small particles (<1µm) that cause particulate emissions (Biedermann & Obernberger, 2005) (Obernberger et al, 1997)

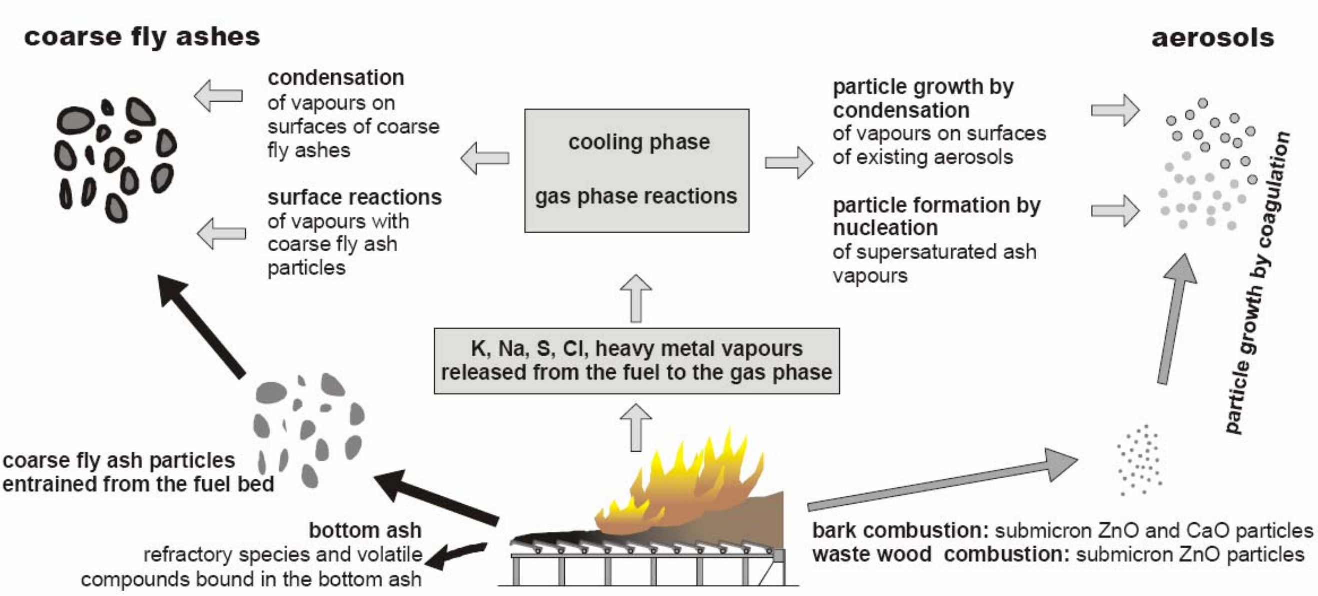


Figure 2: Mechanisms involved in ash formation (Biedermann & Obernberger, 2005)

The following data is the average percentage of the different ash fractions to the total amount of ash in 'straw and cereals' measured in various test runs at large scale plants.

- Bottom ash: 80% - 90%
- Cyclone fly-ash: 3% - 6%
- Filter fly-ash: 5% -10% (Obernberger et al, 1997)

Differences in the amount of ash formed arise due to different combustion technologies, different fly-ash particle sizes and different fly-ash particle densities.

4.2.2 Ash Management

The most relevant flue gas cleaning technology for solid biofuel combustion is dust precipitation. Other technologies include settling chambers, cyclones/multi-cyclones, electrostatic precipitators, baghouse filters, scrubbers and panel bed filters (Obernberger et al, 2004).

Obernberger et al (1997) noted an important fact discovered in their research, which was that cyclones were not suitable for fly-ash precipitation in straw and cereal combustion plants due to the fine and light ash particles formed. Furthermore, they stated that electrostatic precipitators can also fail in straw and cereal combustion plants due to dust resistance and the relatively dry flue gas.

The ash content of a fuel is essential for the selection of appropriate combustion and gas cleaning technology. Fly ash formation, and ash deposits as well as ash storage and utilisation /disposal are all dependent the ash content of a biofuel (Biedermann & Obernberger, 2005). Considerable amounts of plant nutrients are contained in the ashes of solid biofuels, and therefore provide potential utilisation options. This particular concept was explored in a paper entitled 'Ash-related Problems during Biomass Combustion and Possibilities for a Sustainable Ash Utilisation' by Biedermann & Obernberger (2005).

4.3 Slag

4.3.1 Slag Formation

Deposit formation can be classified as either slagging (see earlier section: 2.2.1 'Elements Influencing Ash Formation') or fouling.

- Slagging is refers to the deposits in a molten or highly viscous state, found in the flame section of the furnace and therefore subjected to radiant heat
- Fouling refers to deposits built up largely by species that have vaporised and then condensed, and it occurs in the cooler furnace region where the heat exchanger equipment is located (Paulrud, 2004).

Herbaceous fuels contain Si and K as their principal ash-forming constituents; in addition they also have higher Cl content relative to other biomass fuels. These properties generally lead to severe ash deposition and problems at high or moderate combustion temperatures.

The primary sources of these problems are

a) Reaction of alkali with silica to form alkali silicates that melt or soften at low temperatures (usually > 700ºC)
b) Reaction of alkali with S to form alkali sulphates on combustor heat transfer surfaces (Jenkins et al,1998)

The dominant source of alkali in most biomass fuels is K and it has a central role in both processes. An increasing K concentration in straw tends to accompany increasing ash content, thus indicating an inherent source of K. In addition many of the agricultural by-products contain high K concentrations. (Jenkins et al, 1998)

High K content is the major cause of ash melting behaviour of biomass fuels. Si coupled with K can lead to the formation of low melting silicates, and K can react with S and form sulphates (Paulrud, 2004). Another element, Cl is a significant factor in deposit formation. Research shows that Cl appears to be a facilitator in the transport of alkali from the fuel to surfaces where the alkali forms sulphates (Paulrud, 2004).

Si is often a major element in ash rich fuels, however by itself silica does not present a problem for biomass boilers due to its high melting point (1650°C). However, when K is introduced to form K silicates, the melting point of silica-containing material decreases to less than 750°C (Baxter et al, 1998). In addition, fuels with high silica content also appear to produce a larger volume of ash, which demands special ash handling equipment (Paulrud, 2004).

Baxter et al (1998) list four undesirable effects of deposits:

i. Retardation of heat transfer and the decrease the capacity and efficiency of the boiler
ii. Restriction of flow through the boiler and cause mechanical damage
iii. Accumulation of deposits in hoppers and on grates in forms that are unmanageable by the de-ashing facility, leading to shutdown
iv. Deposits that are associated with corrosion

According to Jenkins et al (1998), the composition of the straw ash is remarkably similar to that of glass, thus helping to explain the rapid sintering, slagging, and fouling observed when burning straw in power boilers designed for wood.

For straw and other agrofuels, there is a higher demand on the combustion equipment compared to wood fuels. This is because the ash content is higher and it contains high levels of Si. For combustions systems burning agrofuels instead of wood fuels, the wear of the equipment and the running expenses will likely be higher (Paulrud, 2004).

Detailed experimentation of combustion of agrofuels is limited however combustion trial tests in the large-scale burner of Reed Canary Grass (RCG) powder took place in 1997 and 2000 (Paulrud, 2004). RCG has high ash content and contains higher levels of Si compared to wood. The results and observations were as follows:

- There were deposits found in the combustion chamber and on convection surfaces
- There were problems transporting the ashes out of the electric filters caused by the large volumes of ashes

- Filters used were not designed to handle large volumes of ash and therefore there were problems with ash removal
- Porous deposits were found on the walls of the boiler (Paulrud, 2004).

One of the main conclusions from these trials demonstrated that ash behaviour needs further research.

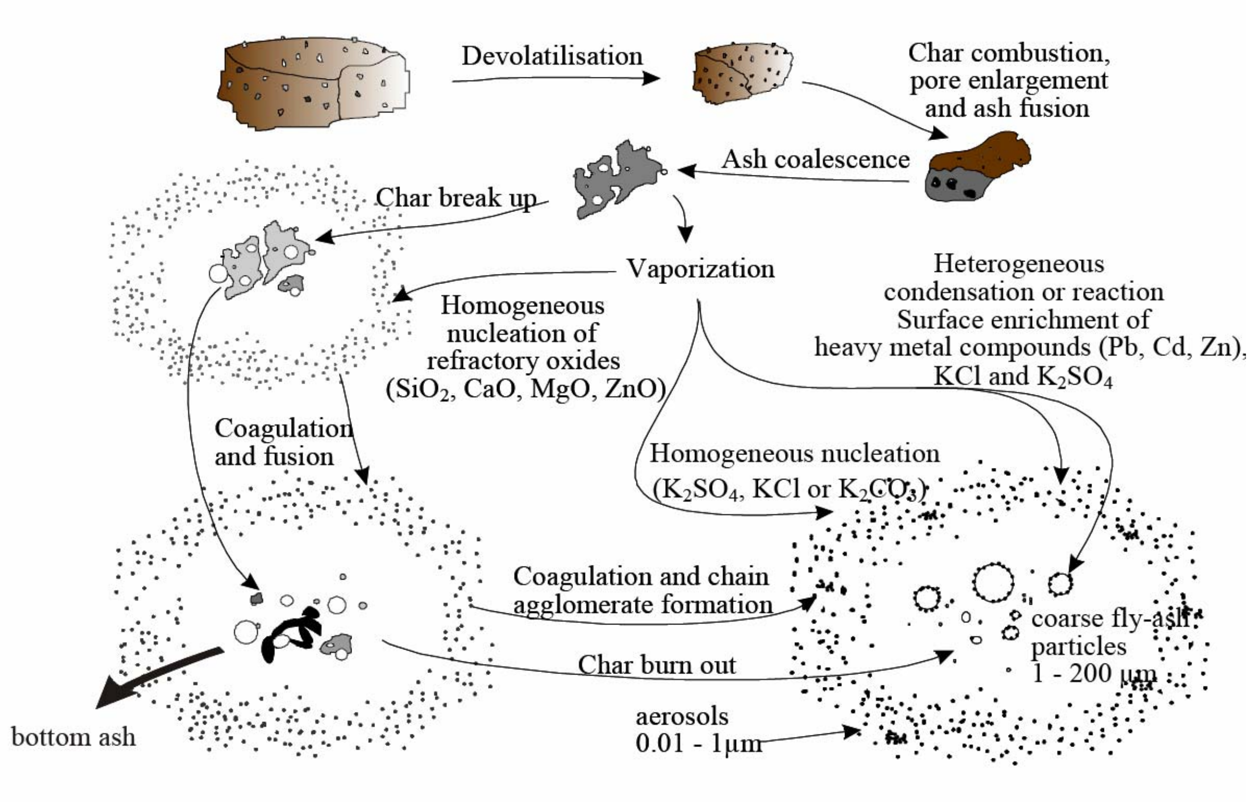


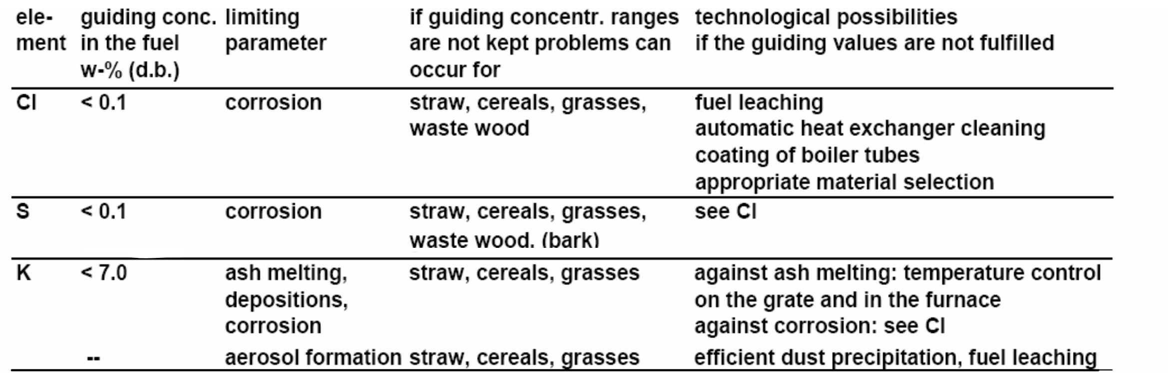
Figure 3: Ash formation and composition (Obernberger et al, 2004)

4.3.2 Slag Prevention

According to Jenkins et al (1998) there are a number of elements involved in reactions leading to ash fouling and slagging, including Si, K, Na, S, Cl, P, Ca, Mg, Fe. The principal mechanisms describing these phenomena in biomass combustors are now reasonably well understood, however the detailed chemistry and means to control or mitigate these processes are far from realised (Jenkins et al, 1998).

Prevention or reduction of slagging is potentially possible in 2 main areas:

- Processing Prevention - Putting measures in place to reduce the slag formation in the combustion process
- Cultivation Prevention - Decreasing levels of K and Si in the feedstock during cultivation



element	guiding conc. in the fuel w-% (d.b.)	limiting parameter	if guiding concentr. ranges are not kept problems can occur for	technological possibilities if the guiding values are not fulfilled
Cl	< 0.1	corrosion	straw, cereals, grasses, waste wood	fuel leaching automatic heat exchanger cleaning coating of boiler tubes appropriate material selection
S	< 0.1	corrosion	straw, cereals, grasses, waste wood. (bark)	see Cl
K	< 7.0	ash melting, depositions, corrosion	straw, cereals, grasses	against ash melting: temperature control on the grate and in the furnace against corrosion: see Cl
	--	aerosol formation	straw, cereals, grasses	efficient dust precipitation, fuel leaching

Figure 4: Guiding values for elements in biomass ashes (Obernberger et al, 2004)

Fig. 4 is a table that shows the recommended ranges for Cl, S and K in order to avoid problematic combustion.

Processing Prevention

The DTi (2006) review how slag formation can be avoided in the burning of grain. The suggested method for burning grain (as opposed to grain 'dust') is a two-stage process:

1) Grain should be pyrolised (chemically decomposed) at a low temperature of less that 700ºC
2) The biogas produced from the pyrolysis must be burned in a separate combustion zone, this secondary combustion process can take place at much higher temperatures

A large combustion chamber is necessary to allow for the separation of combustion zones and this therefore allows differential temperature control which prevents slagging. The air flow is regulated to the primary and secondary combustion zones to maintain temperature.

Cultivation Prevention

Sander (1997) conducted a number of growth trials to investigate whether K and Cl content could be reduced in the growing process. Tests were undertaken to evaluate whether the content of K and Cl could be reduced by choice of variety, however no significant differences were noted between the investigated varieties for spring barley. The influence of growing conditions on the chemical composition of straw was also assessed, but there no relation between soil type and content of K and CI. However, there was a clear correlation between the increasing content of Si and decreasing content of N, with increasing content of clay in the soil. No clear relation between pesticide application and chemical composition of straw was found.

The effect of rainfall on the chemical composition of wheat and barley straw has been investigated. Straw lying on the field after harvest is often subject to rainfall and therefore was sampled and analysed in relation to the accumulated rainfall. 100 mm of rain reduced the content of Cl to a very low level for barley.

Cultivation trials were conducted with Cl-free fertilizer to investigate whether the content of Cl in straw would be reduced. This was done by applying K_2SO_4 instead of KCl as K fertilizer. The Cl content in straw was significantly reduced when the Cl dose from the fertilizer is reduced, but the content of K was not influenced by the applied amount of K fertilizer.

CULTIVATION CONCLUSIONS

K and CI content of biofuels for efficient power production should be as low as possible, a low S and N content is also desirable. Usually straw considerably exceeds the maximum target values of 0.2% K and 0.1% CI normally met by wood chips. The conclusions from the trials recorded by Sander (1997) are as follows:

- There is no correlation between the content of K and CI in straw and soil type, N and P fertilizer dose, pesticide dose and geographic location
- Significant amounts of K and CI are leached from straw lying on the field due post harvest rain
- There is a strong correlation between C1 content in straw and supply of CI with fertilizer;
- Compared to straw, grain has a lower content of ash, K, Ca, Si and CI, but a higher content of N.

The most realistic method for improving straw quality and not interfering with the quality of the barley grain is the application of Cl-free fertilizers.

4.4 Emissions

The DTi (2006) discuss how cereal grains contain a number of chemicals that must be closely monitored and managed to prevent damage to machinery and the environment. High levels of chemicals that include chlorides, nitrates, K- salts and sulphates can be released when cereals are burnt. However, these emissions can be contained to acceptable levels if the temperature of combustion is controlled and cyclones and electrostatic precipitators are installed.

The concentrations of N, S, and Cl in different biofuels are important because they may cause pollutant emissions (see section: 2.2.2 'Elements Influencing Emissions and Corrosion'). Primary pollutants are usually particulate matter, CO, Hydrocarbons C, oxides of N (NO_x, principally NO and NO_2), and oxides of S (SO_x, principally as SO_2) (Jenkins et al, 1998). HCl and other acid gases may also be emitted, in addition to Pb and other heavy metals. Other pollutants formed are products of incomplete combustion such as particles, CO, hydrocarbons including volatile organic compounds (VOC), and polycyclic aromatic hydrocarbons (PAH) (Paulrud, 2004). The composition and amount of ash influences these pollutants, in addition to combustion equipment and process conditions (Jenkins, et al. 1998). However, high concentrations of N, S, and Cl resident in the feedstock are the most influential factor on emissions (Werther et al. 2000).

Emissions of oxides of N and S arise predominantly from N and S in the fuel. S oxides are respiratory irritants, and their effects are enhanced in the presence of particulate matter as they are transported deep within the lung. In addition, both N and S oxides contribute to reactions leading to acid rain. However most commercial biomass combustors operate at temperatures low enough that thermal NO contributes only a small fraction of the total. Uncontrolled NO emissions also depend partly on stoichiometry. The burning and control conditions can have substantial impact on the emission rates of pollutant species according to Jenkins et al, 1998.

Particles that are 10µm or smaller are breathing hazards, as they are retained deep in the alveoli of the lung and most combustion generated particles are less than 1µm aerodynamic particle size. An important issue for grain-dust processing, is that biogenic silica in some materials, such as rice straw, is partly released as fibrous particulate matter which has become of concern recently for lung disease and thus needs careful control (Jenkins et al, 1998).

The DTi (2006) states that grain produces no detectable odour, provided combustion occurs at sufficiently high temperatures in the secondary combustion zone. However problems can occur if a boiler is operating in 'low load' mode where lower combustion temperatures cause incomplete combustion, and this may result in the odours being released from the flue.

Particulate matter includes soot, ash, condensed fumes and absorbed materials including VOC and PAH, these emissions are largely controlled by stoichiometry and proper fuel moisture control (Jenkins et al, 1998).

5) Analysis

5.1 Aims

The analysis of grain-dust was considered to be an essential part of the thesis as it covered new ground. At the time of writing, no data on the chemical makeup and behaviour of grain-dust was available in the public domain. Limited and varied data exists separately for both straw and grain; however the grain-dust produced by the barley drying process was clearly a mixture of both these components. As the values for straw and grain differed significantly, it was necessary to identify the physical and chemical characteristics of the grain-dust samples.

The objectives of the 'grain-dust analysis' were to ascertain experimentally:

- The particle size distribution of the sample
- The moisture content of the sample
- The calorific values of the dust particles and the effect of moisture vapour on that value
- The ash content of the sample
- The percentage of selected elements in the sample

The aim of these experiments was to establish the degree of correlation with existing results for grain and straws and particular patterns of behaviour, irregularities or issues. The European Standards CEN/TS published by the European Committee for Standardisation and British Standards Online[1] were used as reference for the analysis work

The Technical Specifications CEN/TS 15296 covering the analysis of solid biofuels state that generally analysis should be carried out on the air-dried (moist) test samples. However, in order to compare results with alternative sources, it is necessary to express the results on dry basis and sometimes also on some other basis. The bases in common use for solid biofuels are:

- "air-dried"," as determined", - ad
- "as received", "as sampled" or "as delivered" - ar
- "dry" or "dry basis"– db
- "dry, ash free" – daf

---

[1] http://www.bsonline.bsi-global.com/

Most analytical values on a particular basis may be converted to any other basis by multiplying it by the appropriate formula given by the CEN specifications after insertion of the numerical values for the symbols (see Appendices 10.3.1).

The experimental work was largely completed by myself and thus at times lacked appropriate equipment and the necessary experimental in this particular area. Therefore the accuracy of the result is limited and therefore should only be used in conjunction with existing data and not as stand-alone values.

5.2 Particle Size

Paulrud (2004) discusses how particle size can be measured by a variety of methods; the method selected should measure the most relevant size in respect to process under analysis. Techniques that can be used to analysis the particle size of a biofuel are as dry sieving, laser diffraction and image analysis.

Dry sieving

Sieving is one of the oldest methods used for particle size analysis and is still a widely used method as it is a simple and low cost. In commercial fuel dust plants, sieving is also the most common quality control method used (Paulrud, 2004). The sample is sieved through a number of horizontally vibrating sieves, which sort the particles in decreasing size-classes by manual or mechanical means. The particle distribution size is measured by the mass retained in each sieve (Paulrud, 2004). The parameters affect sieving according to Rawle (2001) are:

- sample size
- vibration of sieves and vibration time
- shape of particles
- moisture content

Issues that have to be addressed and accounted for when sieving are as follows:

- Too much dust prolongs the sieving process and affects the result as small particles block the screening surface and reduce the sieve size.
- The vibration of the sieves determines the efficiency of grading of a sample
- The shape of the particles and the shape of the sieve dictates the passage of particles through a sieve
- Narrow, fibrous particles tend to go unimpeded through sieves, but spherical particles tend to blind the sieves and thus affect the particle distribution results.
- Perfect sieves should have openings of equal shape and size, however in reality this might not be the case due to damage.
- Agglomeration (dust gathering or clumping) may be caused by electrostatic charging or moisture (Paulrud, 2004).

In spite of this, sieve analysis is the simplest method for comparing and in the case of grain-dust, separating the same type of the material in the production process. In order to control the production, handling, and combustion process of biomass dust, the European Committee for Standardisation (CEN) has developed a technical specification sieving pulverised biomass fuels (CEN/TS 15149-2:2006) The standard is entitled: Solid biofuels - Methods for the determination of particle size distribution.

5.2.1 Experimental Analysis

There are two main reasons for investigating the particle size of the grain-dust sample.

- The first is to analyse the particle size distribution of the sample in order to compare it to other biofuel samples already used in dust burning equipment. This analysis will help to provide information about whether the sample has to be milled or sieved in order to fulfil equipment recommendations.
- The second reason is to separate the sample into three different fractions, in order to perform a variety of tests on different types of particle matter. Straw and grain have different values for calorific and element constituents. Therefore as grain-dust is a mixture of these two components, samples of different particle size are expected to produce different values, i.e. A larger sized particle fraction would be expected to contain more straw and thus approximate chemical values for straw, alternatively a sample with a small particle size would be expected to produce values similar to grain, as the sample would have a large quantity of small grain particles.

Apparatus

- A variety of rectangular sieves with an effective sieve area of 200 cm^2
- The number of sieves and the aperture sizes was chosen according to the size specification of a dust burner manufacturer, as grain-dust is not yet a specified biofuel, the following sieves were used:
    - 4.0mm, 0.415mm, 2.0mm, 1.0 mm 0,25 mm
- The mechanical device used applied a vibrating movement in 2 dimensions, using a circular motion; however this did not meet the standard which required a device that vibrates in three dimensions.

- A balance measured the mass of the samples to be to the nearest 0.01 g.

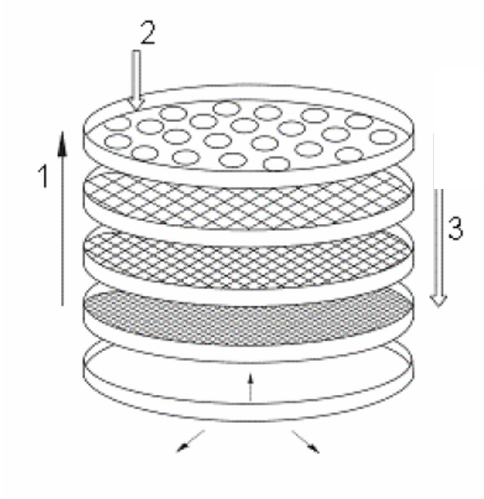


Figure 5: Principle of the sieving operation (CEN/TS 15149-2:2006)

Sample preparation

A number of samples were taken from EOSF's 2005 harvest store. The samples have low moisture content as they have dried out over the course of a year. The moisture content of the material to be sieved was determined latterly according to standards given in CEN/TS 14774-1 or CEN/TS 14774-2.

The minimum size of sample was stated to be 50grams. The standards indicated that to prevent overloading of the screens, samples with a very narrow particle size distribution should be divided into sub-samples of about:

- 0,08 x [effective sieve area in cm^2] g

Therefore a sieve area of 200 cm^2, the mass of the sub-samples should be of about 0,08x200 = 16g.

Some points to note in regard to sample preparation:

- Uniform sub-samples are difficult to achieve as the smaller grain particles settle at the bottom of the large samples
- Consequently sub-samples taken toward the end of the analysis have more dust in them compared to earlier samples

Procedure

- The mechanical vibrating device was assembled with the appropriate sieve sizes with decreasing aperture size ending with the collecting pan.

- The sample was weighed to the nearest 0.01 g and spread the sample in an even layer on the top sieve and covered
- The required minimum sieving time was determined in separate pre-tests, the sieving operation started and continued for 5 minutes for every sub-sample
- The retained net material on each sieve and in the collecting pan was weighed and recorded
- Note: some of the thin particles, which are longer than the hole diameter, passed through the sieve and mixed with the particles in the smaller size fractions which affected the accuracy of the size classification.

5.2.2 Results and Conclusions

The results of the sieved samples are expressed as a percentage of the total mass of all fractions. 5 sub-samples of 16.0 grams were taken from the main sample of grain-dust provided by Highland Grain. Each sample was sieved and the results recorded (see Appendices 10.3.2), the mass of each faction was plotted in the graph entitled 'Results of Size Distribution Analysis' (Fig. 6)

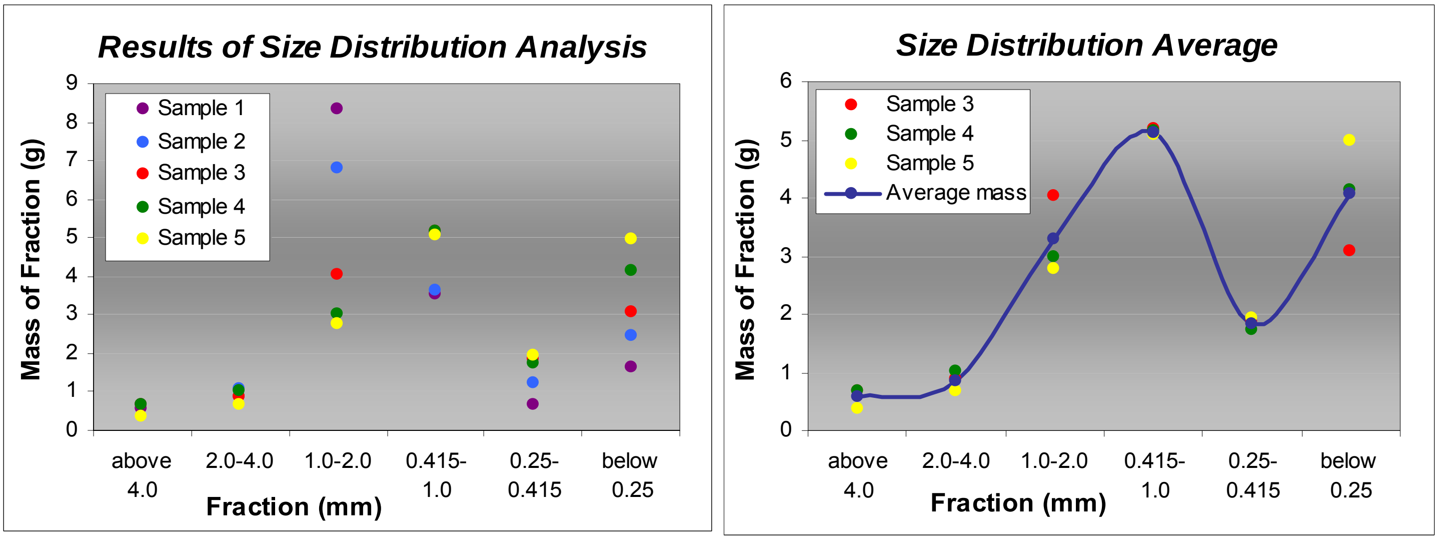


Figure 6: Sample analysis of size distribution

As can be seen from the graph the first two samples have a much larger range of values compared to the latter samples.

The inconsistencies are attributed to experimental error and poor technique that improved thought the progression of the experiments. Therefore the first two samples were neglected in the calculation of the average mass, percentage and distribution of the fractions for the sample.

Therefore the results were re-tabulated using only the latter three results to derive an average mass for each fraction, see table below.

Sieve name	Fraction (mm)	Mass of fraction(g)			Total mass of fractions, samples 3,4&5(g)	Average mass of fraction (g)	% of fraction (based on total mass)
		Sample 3	Sample 4	Sample 5			
1st Sieve (4.0mm)	above 4.0	0.69	0.67	0.36	1.72	0.57	3.64
2nd Sieve (2.0mm)	2.0-4.0	0.87	1.03	0.69	2.59	0.86	5.48
3rd Sieve (1.0mm)	1.0-2.0	4.05	3.00	2.77	9.82	3.27	20.78
4th Sieve (0.415mm)	0.415-1.0	5.18	5.14	5.07	15.39	5.13	32.57
5th Sieve (0.25mm)	0.25-0.415	1.85	1.74	1.94	5.53	1.84	11.70
Collecting pan	below 0.25	3.09	4.13	4.98	12.20	4.07	25.82
Total mass of all fractions		15.73	15.71	15.81	47.25	15.75	100.00

Table 7: Selected Results for size distribution analysis

The difference between the total mass of test portion and the total mass of all fractions as indicated in Table 8 and is smaller than the maximum 2% standard.

Total mass of test portion (g)	47.25
Difference between the total mass of the test portion and the total mass of all fractions of the total test portion (%)	1.563
Moisture content of the sieved sample, in % w/w.	10.5

Table 8: Difference between mass of test portion and total mass of all fractions

Fig. 7 shows the type of particle in each fraction and Fig. 8 shows average particle distribution for a grain-dust sample. The larger fractions raging from 1.0mm to 4.0mm unfortunately do not present an accurate distribution of the particle size. This is due to that the fact than many narrow particles of greater length than the sieve size slipped through the holes of the size.

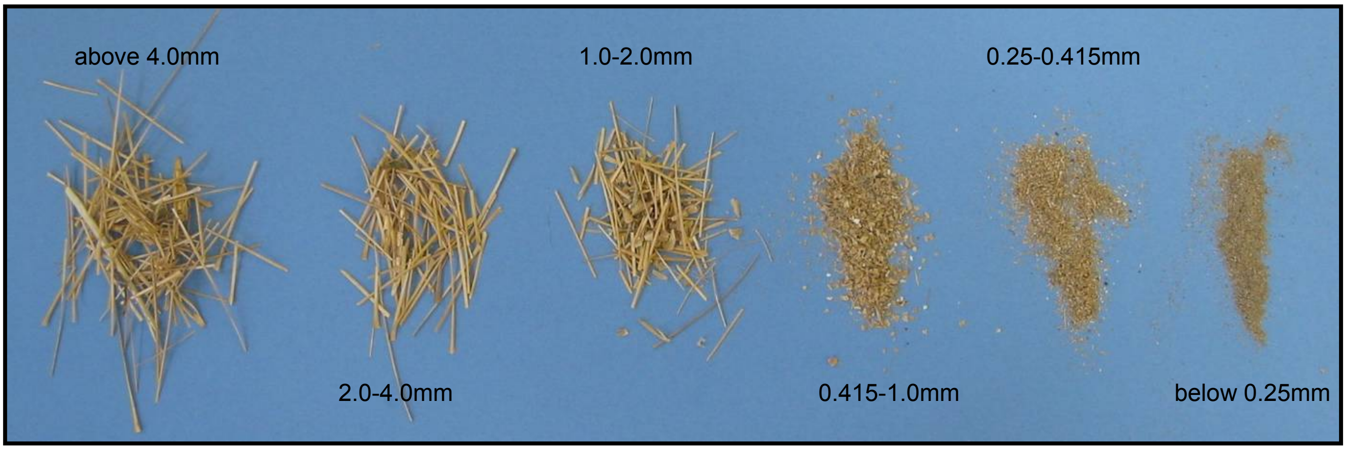


Figure 7: Particle type in different fractions

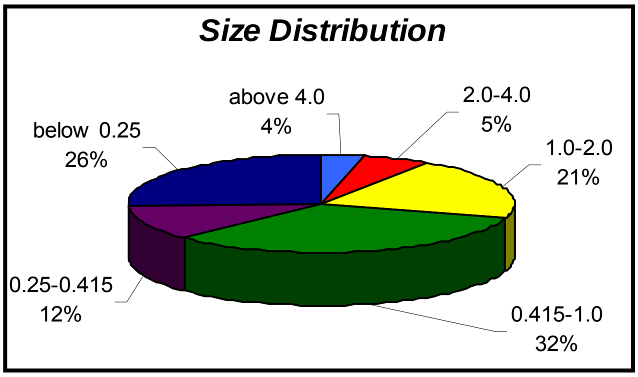


Figure 8: Size distribution of sample (mm)

To further analyse the nature of the sample and its potential use, it is possible to separate the sample into two distinct fractions, dust product and chaff. The dust product is considered to be any particle of size less than 1.0mm and the chaff is any particle larger than 1.0mm. Thus the chaff fraction contains a much higher quantity of straw and the dust fraction contains more grain. As mentioned earlier, within chaff fraction, the size distribution results are not accurate representation of the fraction as thin particles of all sizes were able to pass through the holes of the sieves. However the dust fraction is largely representative of the sample, although some larger particles did pass through the holes.

As can be seen from Fig. 9, in the average Sample 30% of mass is made up of particles larger than 1.0mm, essentially straw, chaff and husk. Whilst 70% of the mass of a sample is grain-dust, particles less than 1.0mm, essentially broken or crushed grain, very small husk/ straw and possibly dirt.

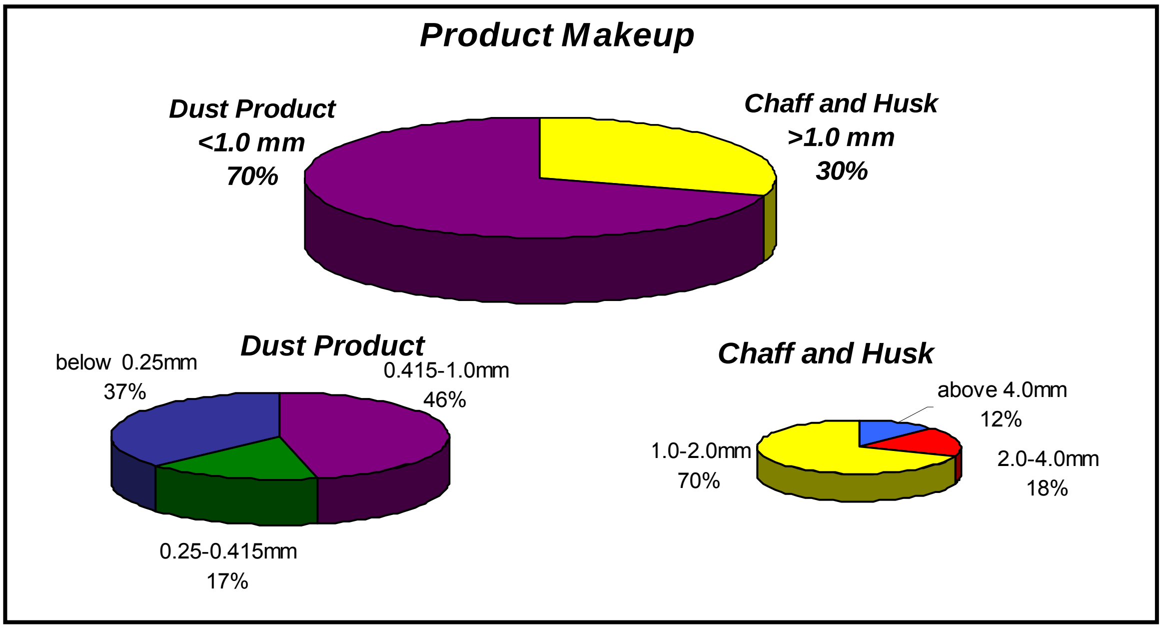


Figure 9: Breakdown of particle size in sample

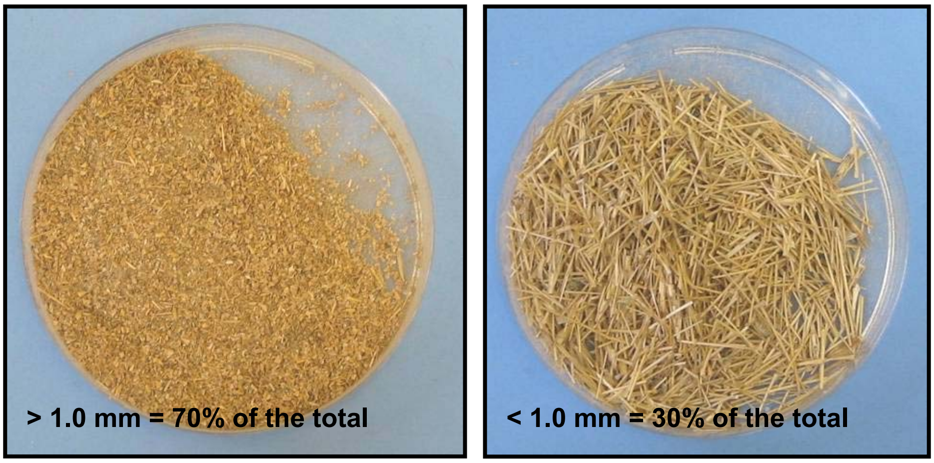


Figure 10: Comparison between mass and density of different samples

Conclusions

It was encouraging to note if it is determined that if the husk and chaff fraction needs to be removed from the sample, it is only about 30% of the sample mass even though it has a much higher density and thus appears to a much larger quantity.

Further experiments will determine whether straw, husk and chaff are a hindrance to burning and therefore it would need to be removed from samples in the future by electrostatic precipitation or by sieving.

3 sample sizes were selected for further analysis:

1. The whole sample, 30% husk/chaff and a 70% dust
2. Any particles smaller than 1.0mm, mixture of dust and fine chaff
3. Any particles smaller than 0.415mm, only dust

A collecting dish and single sieve that only allowed particle smaller than the specified size were used to collect the fraction. The three fractions were sieved several times in order to prevent long thin particle from being included in the smaller size samples

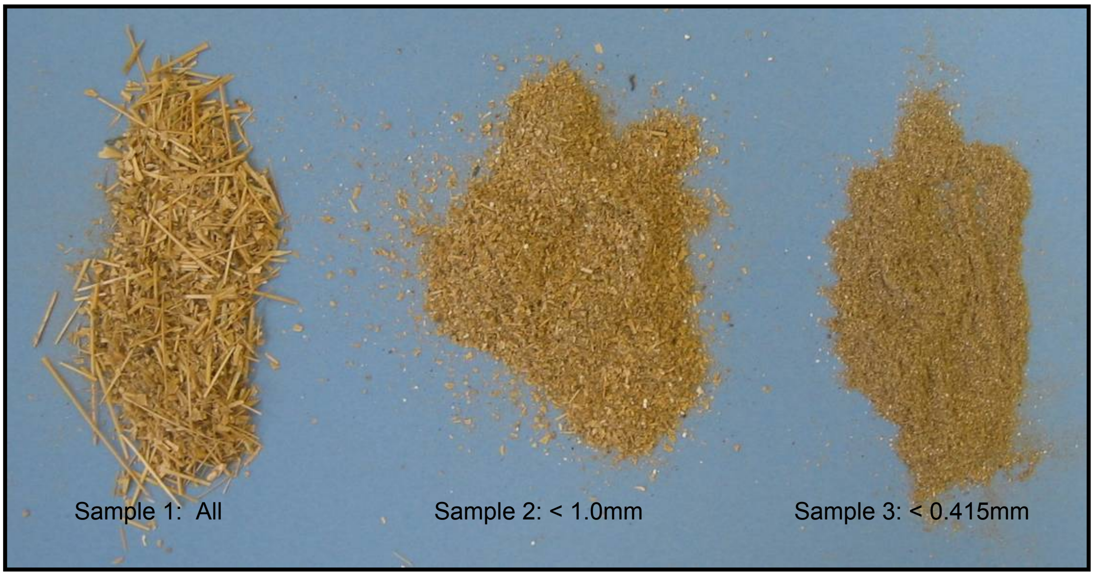


Figure 11: Particle type in three chosen samples

It was interesting to note that the broken and crushed grain particles which are expected to have a higher calorific value were usually larger than 0.415mm and so only a small percentage of them were included in the smallest sample. The smallest sample contained a large quantity of very small particles and it is possible that these particle are dirt/dust particles and not grain, however the decision was taken not to separate them as their nature at the time of testing was not yet known.

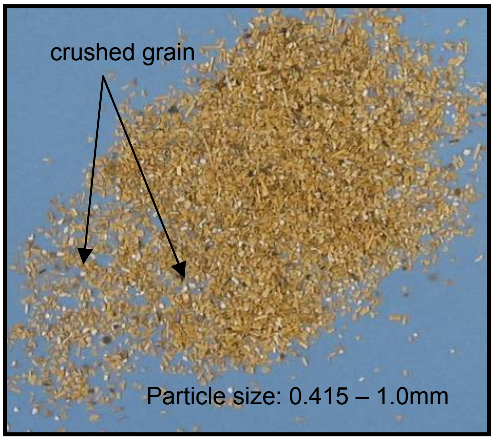


Figure 12: Grain Particles

5.3 Moisture content

Moisture content is the amount of water, or moisture, in a substance expressed as a percentage value (Maier & Bakker-Arkema, 2002). Moisture content on the wet basis expresses the amount of water in the grain as a percent of the total grain weight. The amount of dry weight or dry matter of the grain is the difference between the wet and total weight (Maier & Bakker-Arkema, 2002).

The sample used for the chemical and physical analysis was almost a year old as it had been it was obtained from one of the client companies after the last harvest. Therefore it has lost a significant amount of moisture as it had been in storage. However the value of the moisture content of the sample was necessary for a number of other experiments and in addition provided information about the potential of the grain-dust to dry unaided over the course of a year.

In normal circumstances, the actual moisture content of the grain-dust is thought to be in the region of 11% - 18 % depending on which stage of the drying process it is collected. The moisture content of the grain is about 20% when it arrives at the drying facility and reaches about 12% moisture having passed through the dryers and thus ready for storage.

5.3.1 Experimental Analysis

The following standard was used in the analysis of moisture in the grain-dust samples DD CEN/TS 14774-3:2004, Part 3: Moisture in general analysis sample. This standard was chosen as it was the standard for general analysis rather than high precision moisture content analysis as described in DD CEN/TS 14774-1:2004 or DD CEN/TS 14774-2:2004.

Principle

To analyse the moisture content the biofuel sample is dried at a temperature of (105 ±2°C) and the percentage moisture calculated from the loss in mass of the test sample. This document describes the method of determining the moisture in the analysis sample by drying the sample in an oven.

CEN/TS 14774-3 state that the term moisture content when used with biomass materials can be misleading since untreated biomass frequently contains varying amounts of volatile compounds that may evaporate when determining the moisture content of the general analyses sample by oven drying.

Method

It was decided that only one of the 3 aforementioned varying size samples would be analysed for moisture content. This was because it was assumed the particle size of the samples would not significantly alter the results.

Therefore Sample 2 (all particles smaller than 1.0mm) was chosen for analysis and the experiments were repeated 3 times.

Figure 13: Sample 2 < 1.0mm

The method was as follows:

- An empty weighing dish with its lid, was heated at 105 ±2°C until it achieved a constant mass and then cooled to room temperature in a dessicator, then weighed with its lid to the nearest 0.1 mg.
- About 1g of the analysis sample was added to the weighing dish in an even layer and weighed with the weighing dish and its lid plus to the nearest 0.1 mg.
- The uncovered dish and its lid were then heated together with the sample at (105 ±2)°C until constant in mass.
- Constancy in mass is defined by CEN/TS 14774-3, as a change not exceeding 1 mg in mass during a further period of heating at over a period of 60 min.
- The drying time was established to be 3 hours
- The lid was placed over the dish whilst in the oven, then transferred to a dessicator and cooled to room temperature.
- The dish and its lid with the sample were weighed to the nearest 0.1 mg.

5.3.2 Results and Conclusion

CEN/TS 14774-3 state that for the determination of moisture content, M_{ad}, in the analysis sample, as analysed, expressed as a percentage by mass the following formula can be used:

$$M_{ad} = \frac{(m_2 - m_3)}{(m_2 - m_1)} \times 100 \qquad \text{Equation 1}$$

Where:

- m_1 is the mass in grams of the empty dish plus lid.

- m_2 is the mass in grams of the dish plus lid plus sample before drying.
- m_3 is the mass in grams of the dish plus lid plus sample after drying.

The result for each individual determination was calculated to 2 decimal places and the mean value of the individual results was calculated and rounded to the nearest 0.1%.

	m_1 (g)	**m_2 (g)**	**m_3 (g)**	**M_{ad} (%)**
Sample 2 (>1.0mm)	40.176	41.259	41.144	10.62
	40.464	41.484	41.377	10.49
	40.550	41.736	41.613	10.37
Ave				**10.5**

Table 9: Moisture content of Sample 2

The moisture content of the grain-dust sample was calculated to be 10.5%, and this value was used in all the relevant experiment including the particle size distribution analysis. The value was lower than the typical 12% moisture content, but this was expected due to the period of time that the sample had been allowed to dry out.

5.4 Calorific values

Prime (2005) defines the calorific value of a fuel is the available heat or energy resulting from the complete combustion of the fuel. Net calorific values (NCVs) are considered to be a better indication of the "useful energy" available from the fuel, as Gross calorific values (GCVs) include the energy required to evaporate the water present in the fuel .

A larger proportion of hydrogen (or water) in a fuel is indicated by a greater difference between GCV and NCV, however GCVs are less dependent on fluctuations in moisture content.

According to Obernberger & Thek (2004), the gross calorific values for the different raw material species are such as wood range between 19.8 and 20.7MJ/kg (db) and for straw between 18.6 and 19.0MJ/kg (db).

5.4.1 Experimental Analysis

The following standard DD CEN/TS 14918:2005, 'Solid Biofuels - Method for the determination of calorific value' was used in conjunction with the physical chemistry procedure for measuring the calorific value of the three grain-dust samples.

The determination of the gross calorific value of a solid biofuel at constant volume and in a bomb calorimeter is calibrated by combustion of certified benzoic acid. The result obtained is the gross calorific value of the analysis sample at constant volume with all the water of the combustion products as liquid water.

Terms and definitions

The following terms and definitions were presented in DD CEN/TS 14918:

GROSS CALORIFIC VALUE AT CONSTANT VOLUME

- Absolute value of the specific energy of combustion, in joules, for unit mass of a solid biofuel burned in oxygen in a calorimetric bomb under the conditions specified. The products of combustion are assumed to consist of gaseous O, N, CO_2 and SO_2, of liquid water (in equilibrium with its vapour) saturated with CO_2 under the conditions of the bomb reaction, and of solid ash, all at the reference temperature of 25°c.

NET CALORIFIC VALUE AT CONSTANT VOLUME

- Absolute value of the specific energy of combustion, in joules, for unit mass of the biofuel burned in oxygen under conditions of constant volume and such that all the water of the reaction products remains as water vapour (in a hypothetical state at 0,1 MPa), the other products being as for the gross calorific value, all at the reference temperature.

EFFECTIVE HEAT CAPACITY OF THE CALORIMETER

- Amount of energy required to cause unit corrected temperature rise change in calorimeter temperature caused solely by the processes taking place within the combustion bomb.

Principle

According to DD CEN/TS 14918, the basic principle of the bomb calorimeter is that a weighed portion of the sample of biofuel is burned in high-pressure oxygen in a bomb calorimeter under specified conditions. The effective heat capacity of the calorimeter is determined in calibration experiments by combustion of certified benzoic acid under similar conditions. The temperature rise is recorded from observations of temperature before and after the combustion reaction takes place. The gross calorific value is calculated from the temperature rise and the effective heat capacity of the calorimeter, with allowances made for contributions from ignition energy, combustion of the fuse. The corresponding energy effect between aqueous and gaseous hydrochloric acid can be neglected due to the usually low Cl content of most biofuels (typically less that 0,5 % (m/m) in dry matter).

The net calorific value at constant volume of the biofuel is obtained by calculation from the gross calorific value at constant volume determined on the analysis sample. The calculation of the net calorific value at constant volume requires information about the moisture and H contents of the analysis sample (DD CEN/TS 14918).

Process

The experiment consisted of carrying out quantitatively a combustion reaction (in high-pressure oxygen in the bomb) to defined products of combustion and measuring the change in temperature caused by the total bomb process. The calorimetric determination consisted of two separate experiments, combustion of the calibrant (benzoic acid) and combustion of the biofuel, both under same specified conditions.

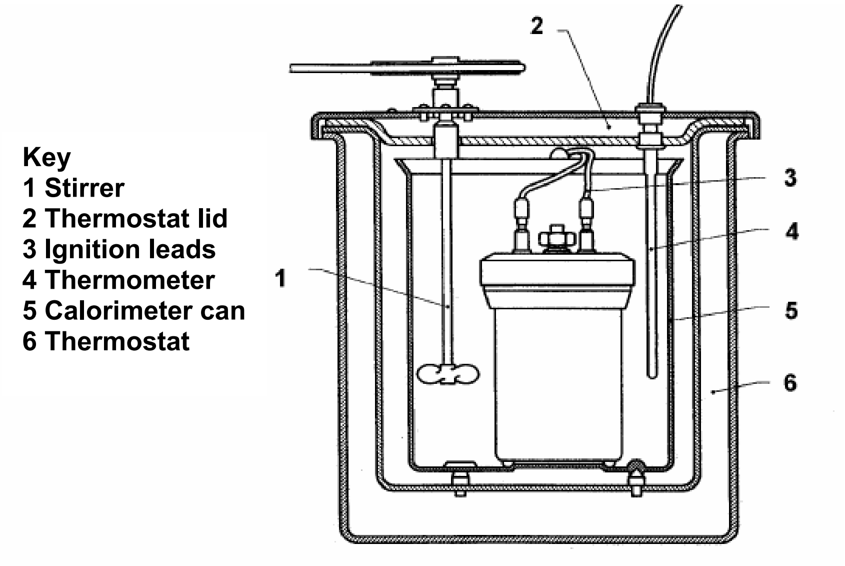


Figure 14: Bomb calorimeter

The calorimeter (see Fig. 14) that was used consisted of the assembled combustion bomb, the calorimeter can the calorimeter stirrer, water, thermometer, and ignition leads. First a calibration sample of benzoic acid was prepared. 1.2g of benzoic acid was pressed into a pellet. A fuse to ignite the sample was created out of nickel-chromium wire (70mm long) was connected to a piece of white cellulose cotton (120mm long) that was tied to the pellet . The combustion comb was assembled and 1cm^3 of distilled was used in the chamber, and 2.1 kg of water was poured into the calorimeter can. 2.5 MPa of oxygen was used to pressurise and fill the bomb before it was assembled.

Due to the low density of solid biofuels they were tested in a pellet form. A pellet of mass (1.3 ± 0.1) g was pressed to produce a compact, unbreakable test piece. Sample 1 provided difficulties with pellet form due to the high straw content.

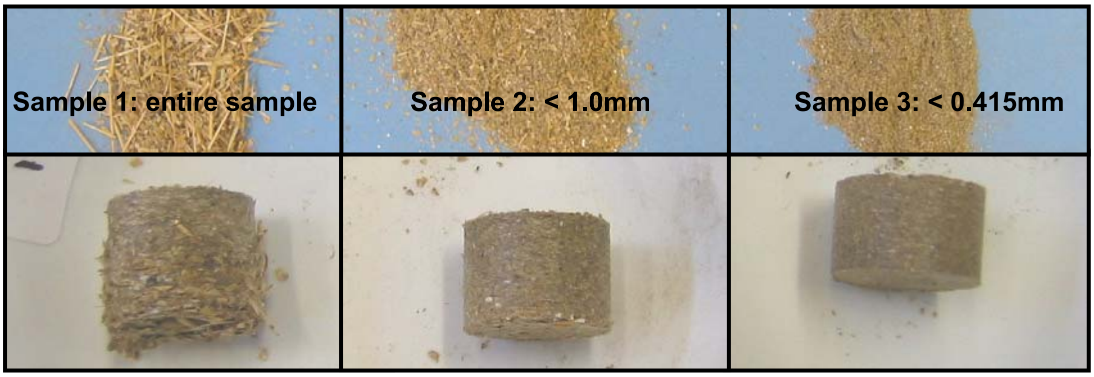


Figure 15: Three different samples and the pellets produced

According to DD CEN/TS 14918, certain biofuels may persistently burn incompletely; “exploding” and/or leaving residues that contain significant amounts of unburned sample or soot. They state that by adding known amounts of an auxiliary material as a combustion aid (e.g. benzoic acid) or by omitting the distilled water from the bomb, or by using a lower oxygen filling pressure, a clean combustion can in most instances be achieved.

The temperature was measured at the beginning of the experiment once it has stabilised then the bomb is ‘fired’. The temperature increased and the highest maximum temperature reached was recorded. When the required temperature readings were completed, the bomb was dismantled. The bomb was examined for signs of incomplete combustion and the any un-reacted pieces of combustible ignition wire were weighed

The test was then repeated for each sample three times, once with a combustion aid in an effort to improve the combustion and reduce the residue that persistently remained.

High Ambient Temperature

A particular hindrance to the calorific tests was the high ambient temperature of the room and the temperature of the tap water in the used to regulate the combustion system. This was due to temperatures reaching 30ºC during that particular day and throughout the week. The ambient temperature of the water was about 23ºC rather than the required 20ºC; and it continued to rise with no aid due to the warm room temperature. This affected the accuracy of results, as even 10 minutes after exploding the bomb there were still changes in temperature.

5.4.2 Results

It was expected that Sample 1 would have the lowest calorific values as it had the highest percentage of straw. Samples 2 and 3 supposedly had higher grain-dust content and therefore it was expected that their calorific values would be higher as grain usually has a higher calorific value than straw. However this was not the case, but the tests did reveal a number of interesting points.

See following page for calculations

The results were calculated as follows:

if *heat released by b/acid = (wt of b/acid x CV)*
and *total amt of heat released = amt fr b/acid + amt fr wire/cotton*
then *total amt of heat released = effective heat capacity x T rise*

For B/acid : amt fr b/acid + amt fr wire/cotton = effective heat capacity x T rise
⇒ (wt of b/acid x CV + wt of wire/cotton x CV) /T rise = effective heat capacity

For Pellet : (wt of pellet x CV) + (wt of wire/cotton x CV) /T rise = effective heat capacity

gross calorific value (at constant volume) = $q_{v,gr}$

temperature rise = ΔT	*cotton* = x
heat released = Q	*pellet* = p
mass = m	*nickel/chrome wire* = w
effective heat capacity = ε	*benzoic acid* = b

$$Q_b = m_b q_{v,b} \quad Q_p = m_p q_{v,p} \quad Q_w = m_w q_{v,w} \quad Q_x = m_x q_{v,x}$$

$$Q_{total} = Q_b + Q_w + Q_x = \varepsilon \Delta T$$

$$\Rightarrow \varepsilon = \frac{(Q_b + Q_w + Q_x)}{\Delta T} \quad and \quad \varepsilon = \frac{(Q_p + Q_w + Q_x)}{\Delta T}$$

$$\therefore Q_p = \varepsilon \Delta T - Q_w - Q_x = m_p q_{v,p}$$

$$\Rightarrow q_{v,gr} = q_{v,p} = \frac{\varepsilon \Delta T - Q_w - Q_x}{m_p}$$

N.B. $m_w = m_{w1} - m_{w2}$
The heat contribution from the formation of nitric acid from liqid water and gaseous N and O is not included in the calculation

To calculate the gross calorific value at constant volume for the dry fuel (dry basis, in dry matter) use the following equation :

$$q_{v,gr,db} = q_{v,gr} \times \frac{100}{100 - M_{ad}}$$

where :
$q_{v,gr,db}$ *is the gross calorific value at constant volume of the dry (moisture - free) fuel (J/g)*
M_{ad} *is the moisture content in the analysis sample, in percentage by mass*

Test	Sample	Mass [g]			Temperature [°C]			Heat released (Q = mq_{gr}) [MJ]		Gross Calorific Value (q_{gr}) [MJ/kg]	
		Pellet (m_p)	Cotton (m_x)	Wire (m_{w1}-m_{w2})	T_1	T_2	ΔT	Wire (Q_w)	Cotton (Q_x)	As received (q_{gr})	Dry basis ($q_{gr,db}$)
Calibration		1.196	0.076	0.002	22.17	25.22	3.05	0.003	1.330	26.452	/
Test 1	**1**	1.505	0.073	0.007	21.38	23.84	2.46	0.010	1.278	16.814	18.786
	2	1.152	0.077	0.003	21.72	23.43	1.71	0.004	1.348	14.872	16.617
	3	1.763	0.079	0.002	21.88	24.23	2.35	0.003	1.383	13.623	15.221
Test 2 with b/acid	**1**	1.373	0.075	0.001	22.55	25.38	2.83	0.001	1.313	20.787	23.226
	2	1.407	0.077	0.003	23.40	25.94	2.54	0.004	1.348	17.749	19.832
	3	1.393	0.077	0.002	23.13	25.32	2.19	0.003	1.348	14.952	16.706
Test 3	**1**	1.270	0.076	0.003	22.81	24.95	2.14	0.004	1.330	17.164	19.178
	2	1.274	0.074	0.004	22.52	24.48	1.96	0.006	1.295	15.609	17.441
	3	1.285	0.078	0.003	21.72	23.51	1.79	0.004	1.365	13.992	15.634

Table 10: Results of calorific tests

See complete results in Appendices 10.3.5.

First Test

The first set of tests on samples 1, 2 and 3 revealed a persistent problem and that was that a deposit remained for each of the three samples when combusted. DD CEN/TS 14918 state that the test should be discarded if unburned sample or any soot deposit is visible. In the first set of tests a crystalline deposit formed, however some of the sample remained unburned and thus lowered the calorific value of the tests. However it can be seen from the results than there is a decreasing trend of the magnitude of calorific value from Sample 1 through to 3.

Second Test with Combustion Aid

It was decided to use a combustion aid for the second set of tests in an effort to get rid of the deposits and to completely burn the samples. Samples of 1.3 grams from each grain-dust fraction were weighed. 0.13grams (10%) benzoic acid was added to each sample. Each sample was mixed and then pelletised, however homogeneity in the sample was difficult to achieve. The calorific tests were then completed in exactly the same method as the first set of tests.

However a similar amount of deposit still remained for each sample, although it was interesting to note there appeared to be no unburned residue as there was in the first set of tests. When the calorific values were calculated for each sample, and the effect of the benzoic acid taken into account, the calorific values were substantially higher.

Third Test

As the benzoic acid had not been able removed the ash deposit from the samples, the decision was taken to revert to the first method and negate the use of the combustion aid. This was done in order to observe whether the results were reproducible (difference of 300J/g) and or repeatable (difference of 120J/g).

However this was not the case, as can be seen from Fig. 16, the results were significantly higher although as similar trend was followed. The difference is likely due to the warmer temperatures of both the water and the room due to warmer afternoon temperatures compared to the earlier tests in the morning. In addition, experimental technique used had also improved through out the course of the day and this might account for a portion of the difference.

Results Summary

Gross Calorific Value (q_{gr}) [MJ/kg db]			
Sample No.	**Test 1**	**Test 2 (with b/acid)**	**Test 3**
Sample 1 (entire sample)	18.786	23.226	19.178
Sample 2 (< 1.0mm)	16.617	19.832	17.441
Sample 3 (< 0.5mm)	15.221	16.706	15.634

Table 11: Summary of calorific results

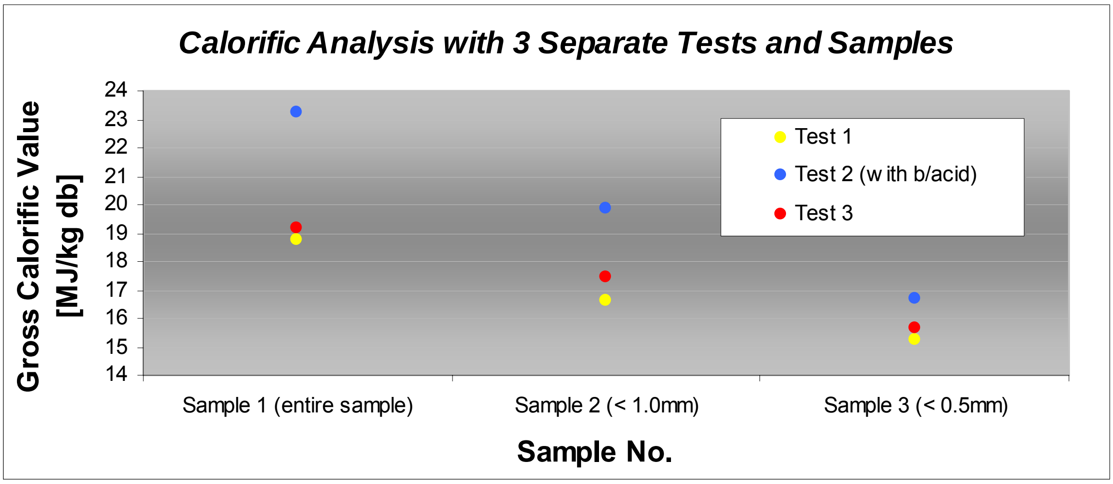


Figure 16: Graph of calorific results for 3 separate tests and 3 separate samples

5.4.3 Conclusions

It is interesting to note the results were not what were initially expected. Sample 3 was expected to have the lowest calorific values and Sample 1 had the highest values, but the inverse was consistently true for all three tests.

Deposits

Each set of tests produced varying deposits that were different for each sample, see following Fig. 17.

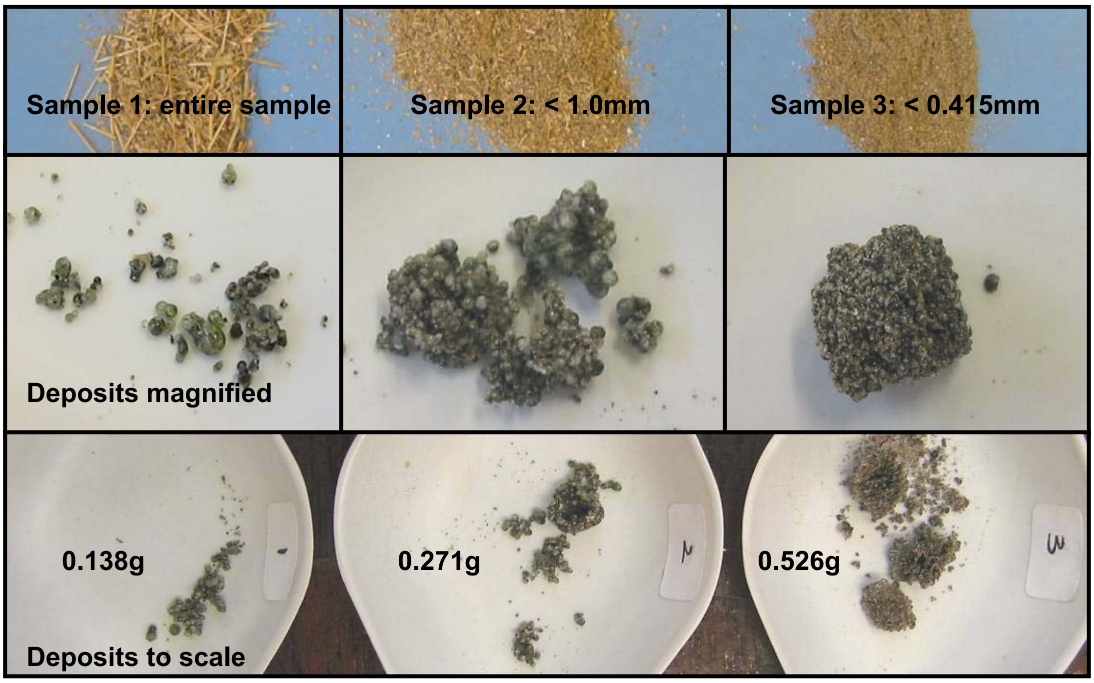


Figure 17: Various deposits from each sample

As can be seen in Fig. 17, each sample produced significant deposits after combustion with the amount of deposit increasing through samples 1 to 3. The deposits were latterly placed in the furnace at 1000°C to observe whether there was a reduction in weight, which would suggest unburnt matter. The mass underwent a varying 3-7% decrease in each of the three samples, suggesting some unburnt matter existed but over 90% of the deposit had already been combusted. Analysis and descriptions of the deposit formed from each sample can be summarised as follows:

- Sample 1 (all) – smallest amount of deposit, large bulbous glassy crystals formed, green/grey in colour
- Sample 2 (<1.0mm) – 50% increase in mass of deposit compared to Sample 1, smaller bulbous crystals formed, greyer in colour
- Sample 3 (<0.5mm) - 50% increase in mass of deposit compared to Sample 2, therefore 4 times the mass of Sample 1, very small circular crystals formed, grey in colour, pellet remained whole

Although the samples appear to have been completely burnt there is still a substantial amount of residue remaining and this is assumed to be dirt, as dirt does not burn. The resulting deposits has led to the hypothesis that a large amount of dirt/dust as opposed to grain-dust is present in the two smaller particle samples, samples 2 and 3, which is why they burn with a significantly lower calorific values and have much higher residues. The amount of dirt in the smaller sample poses a significant problem for effective and efficient burning. However a logical assumption for the large portion of the dirt in the samples is the extended period of exposed storage the samples had undergone before analysis, which may have increased the amount of dust allowed to settle on the samples.

Comparison with Current Data

As the third series of test with each of the samples was considered to be the most accurate, those results were compared with a variety of data from other sources.

The deposits from samples 2 and 3 rendered them invalid due to the high dirt content present, thus lowering their actual calorific value, so for the purposes of comparison Sample 1 was used. A calorific value of 19.18 MJ/kg is comparable to existing data which varies significantly, although its value is potentially higher than it should be due to the high ambient temperatures at the time of measurement.

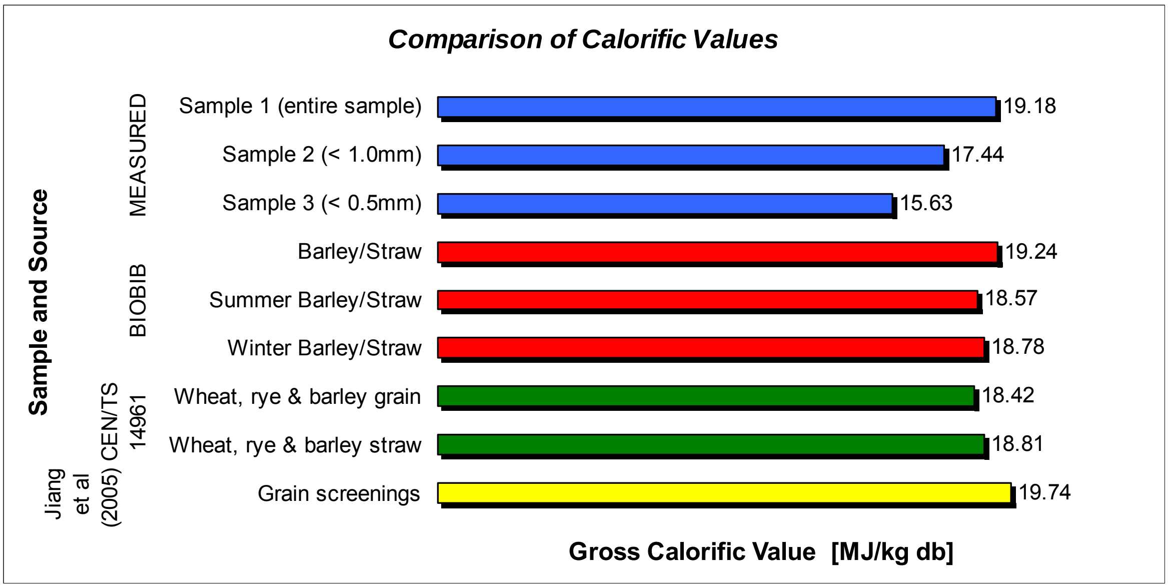


Figure 18: Comparison of calorific values using alternative data sources

In the Analysis Summary, the gross calorific values are converted into net calorific values using values for hydrogen and moisture content for a more detailed comparison. (see Appendices 10.3.4 and 10.3.6). Calorific values are also compared and discussed further in the latter sections of the project.

5.5 Ash Content

Obernberger et al (1996) undertook a number of studies and investigated the ash content of different biofuels in respect to their total weight on a dry basis (wt% [db]):

- Straw (Winter wheat)- 6.7%
- Cereals (Triticale)– 5.3%
- Bark (Spruce) - 7.0%
- Wood chips (Spruce) - 1.1%

Ash Melting Behaviour

According to Biedermann & Obernberger (2005), straw, cereal, grasses and grain ashes, which contain low concentrations of Ca and high concentrations of Si and K, start to sinter and melt at significantly lower temperatures than ashes from wood fuels. Hard deposit formation furnace walls or heat exchanger tubes may result from melts occurring in fly ash particles. Alkali and heavy metal salt mixtures (mixtures of alkali chlorides and sulphates with Zn chlorides) can accelerate hard deposit formation by sticky fly ash articles. (Biedermann & Obernberger, 2005)

Paulrud (2004) discusses how the melting behaviour of ashes can be estimated using a variety of theoretical, empirical, and laboratory methods. Öhman (1999) described several of these methods. Ash fusion standard tests are the most commonly used; additional tests include compression strength tests, chemical equilibrium model calculations, high-temperature light microscopy and bench-scale fluidised-bed combustion tests. However it was not possible to undertake tests to examine the melting behaviour of ash for the purposes of this project but nevertheless ash melting behaviour is a crucial area for determining whether grain-dust could be used as a biofuel.

5.5.1 Experimental Analysis

The following standard was used in the analysis of ash content in the grain-dust samples, DD CEN/TS 14775:2004 Solid Biofuels - Method for the determination of ash content.

Ash content (dry basis) is defined by CEN/TS 14775 as the mass of inorganic residue remaining after ignition of a fuel under specified conditions expressed as a percentage of the mass of the dry matter in the fuel

Principle

According to CEN/TS 14775 the ash content is determined by calculation from the mass of the residue remaining after the sample is heated in air under rigidly controlled conditions of time, sample weight and equipment specifications to a controlled temperature of 550±10ºC.

Method

The ash content determination tests were carried out 3 times on the three different sized samples. The larger sample was ground until it had a particle size of less than 1.0mm

- An empty porcelain dish was heated in the furnace to (550 ± 10) °C for 60 min, then removed the dish from the furnace, cooled and weighed
- The general analysis sample was mixed and then 1.0 g of sample were spread in an even layer over the bottom surface of the dish, and then weighed
- The sample in the furnace was heated as follows:
    - The furnace temperature was raised evenly to 250 °C over a period of 50 minutes (i.e. a rise of 5 °C/min).
    - This temperature was maintained for 60 min to allow the volatiles to leave the sample before ignition.
    - The furnace temperature was then raised evenly to 550±10ºC over either a period of 60 minutes, and kept level for at least 120 min.
- The ash and the dish were cooled and weighed to the nearest 0.1 mg as soon as the ambient temperature was reached

5.5.2 Results and Conclusion

CEN/TS 14775 state that the ash content on dry basis, A_d, of the sample expressed as a percentage by mass on a dry basis is calculated using the following formula:

where:

$$A_{db} = \frac{(m_3 - m_1)}{(m_2 - m_1)} \times 100 \times \frac{100}{100 - M_{ad}}$$

Equation 2

- m_1 is the mass, in grams, of empty dish;
- m_2 is the mass, in grams, of the dish plus the test sample;
- m_3 is the mass, in grams, of the dish plus ash;
- M_{ad} is the % moisture content of the test sample used for determination (10.5%)

Sample Type	1 (entire sample)			2 (< 1.0mm)			3 (< 0.415mm)		
Trials	1	2	3	1	2	3	1	2	3
m_1 (g)	41.045	40.611	40.642	39.692	39.771	40.062	40.108	39.646	40.007
m_2 (g)	42.088	41.581	41.724	40.683	40.774	41.388	41.594	41.065	41.272
m_3 (g)	41.116	40.673	40.723	39.893	39.984	40.351	40.676	40.172	40.474
A_{db} (%)	7.640	7.188	8.368	22.711	23.680	24.326	42.701	41.386	41.275
Average A_{db} (%)	7.7			23.6			41.8		

Table 12: Ash Content

The results showed that Sample 1 had the lowest ash content and Sample 3 had the highest ash content:

- Sample 1 (all) – 7.7 % wt (db)
- Sample 2 (<1.0mm – 23.6 % wt (db)
- Sample 3 (<0.5mm) – 41.8 % wt (db)

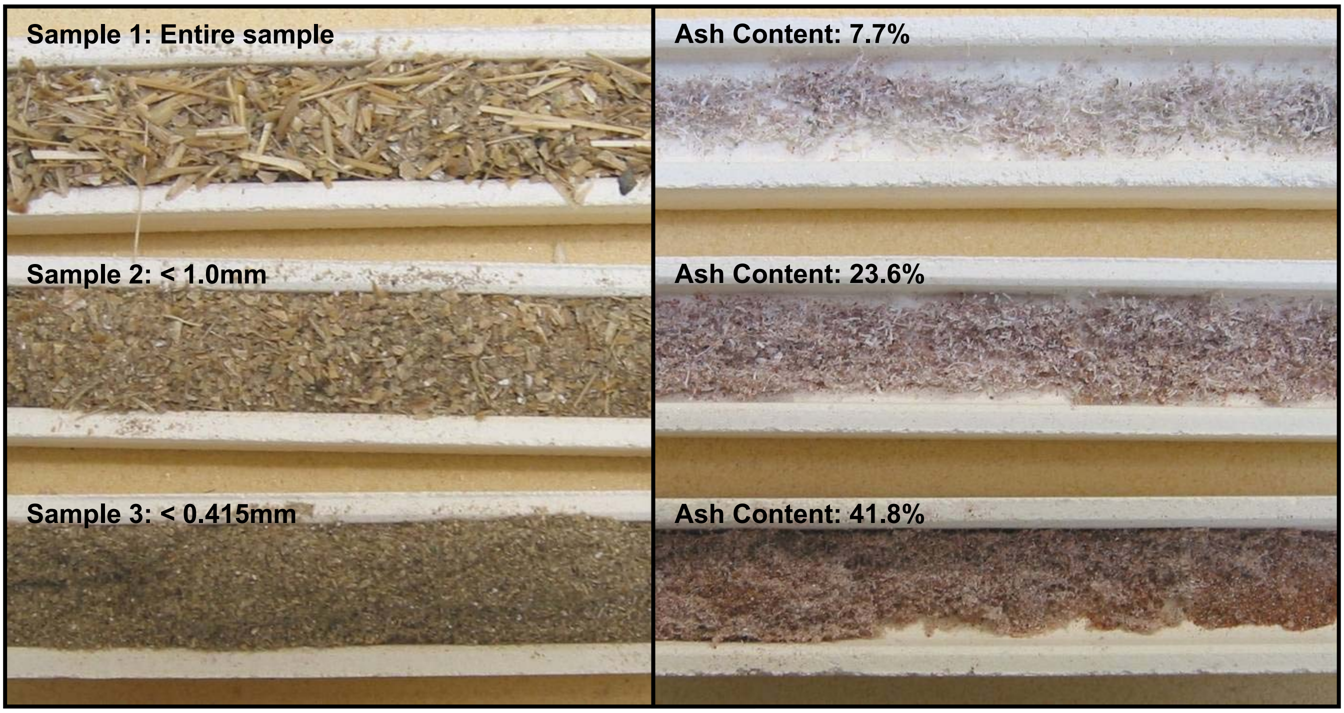


Figure 19: Various samples and their ash contents

As can be seen from the Fig.19, Sample 1 has significantly lower ash content than Sample 2 and 3. At the beginning of the analysis, this was initially unforeseen, however following the calorific tests results which revealed that Sample 3 left a much larger deposit than samples 2 and 1, it was anticipated that a similar proportion of deposits/ash would be produced. The assumed cause behind this is the amount of dirt that is present in the samples. As dirt does not combust it remains in the ash along with the fly ash. Although all the samples contain dirt there is a much higher proportion of dirt to grain product in the smaller samples, as can be seen from the photos, note the red-tinted ash.

One further test was undertaken to establish the ash content of a sample from which small particles and therefore the dirt fraction had been removed. The particle size of the final fraction was between 1.0mm and 0.2 mm. The test was conducted under similar conditions to the previous tests however only one trial was used for each sample size.

Sample Type	1 (entire sample)	2 (< 1.0mm)	3 (< 0.415mm)	4 (0.415-1.0mm)
m_1 (g)	40.695	40.619	40.575	40.541
m_2 (g)	41.552	41.490	41.788	41.292
m_3 (g)	40.754	40.794	41.041	40.556
A_d (%)	7.7	22.4	42.9	2.2

Table 13: Ash content with additional sample type

As can be seen from Table 13 and Fig. 20, sample 4 has significantly less ash than the other

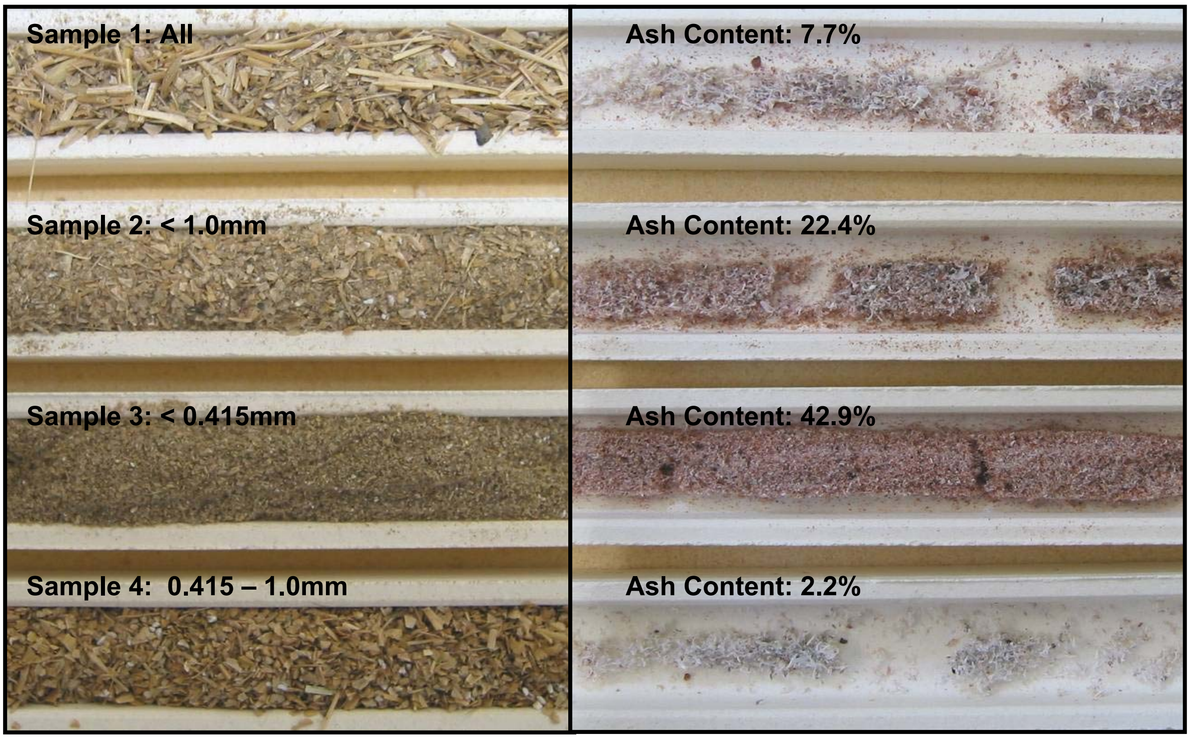


Figure 20: Photos of ash content with additional sample type

three samples. The reason for this is that the dust fraction which is generally smaller than 0.415mm has been removed and is not part of the sample, in addition there is less chaff and husk as that fraction is usually larger than 1.0mm. Therefore a grain sample with a much higher portion of grain compared to straw and dirt can reduce the mass of ash by up to 40%.

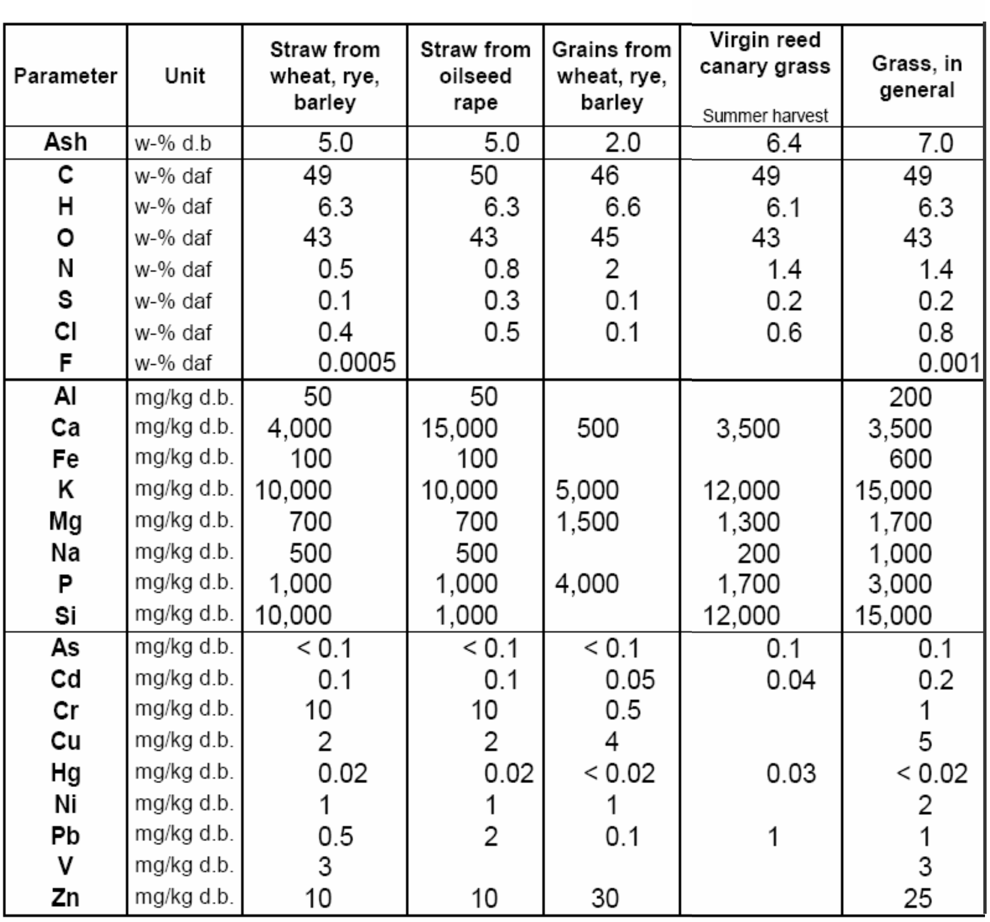
5.6 Elemental Analysis

The C, H, O, N and Cl content of the three samples was analysed by microanalysis laboratory at Strathclyde. The S content of the samples was considered too small to detect. Full results can found in the Appendices 10.3.3.

Table 14 contains typical mean values for the chemical composition of herbaceous fuels obtained from European research work (Biedermann & Obernberger, 2005).

The table contains values for a number of different biofuels. The major element were analysed on a dry, ash-free basis and the minor elements were analysed on a dry basis.

As can be seen from the table barley straw contains more than twice the amount of ash that barley grain contains. Values for C, H, and O are similar, however barley grain contains 4 times the amount of nitrogen compared to straw which bears significance for NO_x emissions, but straw has four times the amount of Cl compared to grain.



Parameter	Unit	Straw from wheat, rye, barley	Straw from oilseed rape	Grains from wheat, rye, barley	Virgin reed canary grass Summer harvest	Grass, in general
Ash	w-% d.b	5.0	5.0	2.0	6.4	7.0
C	w-% daf	49	50	46	49	49
H	w-% daf	6.3	6.3	6.6	6.1	6.3
O	w-% daf	43	43	45	43	43
N	w-% daf	0.5	0.8	2	1.4	1.4
S	w-% daf	0.1	0.3	0.1	0.2	0.2
Cl	w-% daf	0.4	0.5	0.1	0.6	0.8
F	w-% daf	0.0005				0.001
Al	mg/kg d.b.	50	50			200
Ca	mg/kg d.b.	4,000	15,000	500	3,500	3,500
Fe	mg/kg d.b.	100	100			600
K	mg/kg d.b.	10,000	10,000	5,000	12,000	15,000
Mg	mg/kg d.b.	700	700	1,500	1,300	1,700
Na	mg/kg d.b.	500	500		200	1,000
P	mg/kg d.b.	1,000	1,000	4,000	1,700	3,000
Si	mg/kg d.b.	10,000	1,000		12,000	15,000
As	mg/kg d.b.	< 0.1	< 0.1	< 0.1	0.1	0.1
Cd	mg/kg d.b.	0.1	0.1	0.05	0.04	0.2
Cr	mg/kg d.b.	10	10	0.5		1
Cu	mg/kg d.b.	2	2	4		5
Hg	mg/kg d.b.	0.02	0.02	< 0.02	0.03	< 0.02
Ni	mg/kg d.b.	1	1	1		2
Pb	mg/kg d.b.	0.5	2	0.1	1	1
V	mg/kg d.b.	3				3
Zn	mg/kg d.b.	10	10	30		25

Table 14: Chemical composition of herbaceous fuels (Obernberger et al, 2004)

5.6.1 Carbon, Hydrogen, and Oxygen Content

C, H and O are the main components of biofuels. C and H are oxidised during combustion and form CO_2 and H_2O through exothermic reactions. C and H increase the gross calorific value (GCV) but O decreases it. In addition H influences the net calorific value (NCV) due to water formation. As wood fuels have a higher C content than herbaceous fuels, wood fuels consequently have a slightly higher GCV (Obernberger et al (2004).The organically bound O provides a part of the O necessary for the combustion process, additional O must be supplied by air injection.

Although CO_2 is a major product of complete combustion, its emissions from biofuels is regarded as CO_2-neutral if sustainable utilisation is used. Incomplete combustion leads to emissions of unburned carbon based pollutants such as carbon monoxide, hydrocarbons, polycyclic aromatic hydrocarbons, tar and soot (Obernberger et al (2004).

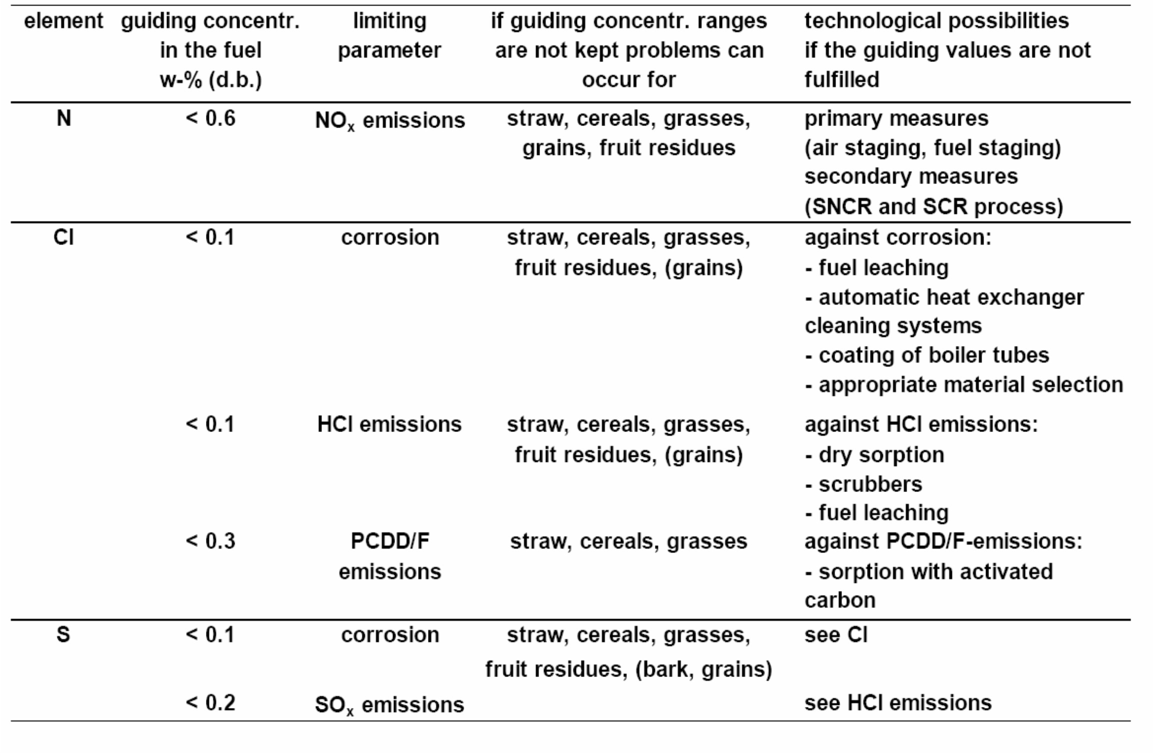
5.6.2 Chlorine, Nitrogen and Sulphur Content

N in the fuel is responsible NO_x formation and emissions. During combustion N is converted to N_2 and Nitric oxides (NO_x [NO, NO_2])

Significantly higher amounts of Cl are present in herbaceous biofuels compared of wood which generally has very low Cl content. Cl contained in biofuels mainly forms gaseous HCl, Cl or alkali chlorides such as KCl and NaCl during combustion. Biedermann & Obernberger (2005) explain that due to the subsequent cooling of the flue gas in the boiler section of the combustion plant, Cl salts form particles or condense on the heat exchangers surfaces or on fly ash particles. They claim that in straw or cereals combustion 80 to 85% of the total Cl released is embedded in the ash compared to in the 40 to 80% in the case of wood chip or bark combustion.

S and Cl form gaseous and solid compounds, and a portion of the elements are bound to the ash by formation of chlorides and sulphates. In addition, S and Cl compounds influence the melting and fouling behaviour of fly-ash particles and can cause corrosion in the boiler. The subsequent cooling of the flue gas in the boiler section of the combustion plant causes SO to form sulphates and condenses on the heat exchanger surfaces or forms fine fly ash particles.

The following table is a set of guidelines for the recommended maximum concentrations of N, Cl, and S in order to avoid the associated issues. (Obernberger et al (2004).



element	guiding concentr. in the fuel w-% (d.b.)	limiting parameter	if guiding concentr. ranges are not kept problems can occur for	technological possibilities if the guiding values are not fulfilled
N	< 0.6	NO_x emissions	straw, cereals, grasses, grains, fruit residues	primary measures (air staging, fuel staging) secondary measures (SNCR and SCR process)
Cl	< 0.1	corrosion	straw, cereals, grasses, fruit residues, (grains)	against corrosion: - fuel leaching - automatic heat exchanger cleaning systems - coating of boiler tubes - appropriate material selection
	< 0.1	HCl emissions	straw, cereals, grasses, fruit residues, (grains)	against HCl emissions: - dry sorption - scrubbers - fuel leaching
	< 0.3	PCDD/F emissions	straw, cereals, grasses	against PCDD/F-emissions: - sorption with activated carbon
S	< 0.1	corrosion	straw, cereals, grasses, fruit residues, (bark, grains)	see Cl
	< 0.2	SO_x emissions		see HCl emissions

Table 15: Guiding values and ranges for unproblematic combustion (Obernberger et al (2004)

5.6.3 Results and Conclusions

The lab was given the 3 samples of grain-dust. They performed microanalysis on each of the samples as they were (air dried). For C, H, N and Cl, 3 trials were completed for each of the 3 samples. The lab noted that due the mixed content of the samples, the matter contained was not homogenous and therefore results differed. The results from each of the trials of the 3 samples were averaged and tabulated as follows (Full results can be found in the Appendices 10.3.3):

Sample Type	**C**	**H**	**N**	**Cl**
	wt -% (ad, air dried)			
Sample 1 (entire sample)	38.32	6.06	0.75	0.61
Sample 2 (< 1.0mm)	38.18	5.98	0.90	0.28
Sample 3 (< 0.5mm)	26.80	4.28	0.84	0.11

Table 16: Average of elemental results received from the lab for C, H, N and Cl

As most results for elemental analysis for biofuels printed in journals and academic papers are recorded on a dry basis (db) or dry, ash free basis (daf) the results received from the lab were converted into these formats for comparison using guidelines from CEN/TS 15296.

Type	Moisture	Ash		C			H			N			Cl			O		
Basis	M_{ad}	A_{ad}	A_{db}	wt - %			wt - %			wt - %			wt - %			by difference		
	ad	ad	db	ad	db	daf	ad	db	daf	ad	db	daf	ad	db	daf	ad	db	daf
1	10.50	6.92	7.73	38.3	42.8	46.4	6.06	6.77	7.34	0.75	0.84	0.91	0.61	0.68	0.74	47.3	41.2	44.6
2	10.50	21.1	23.6	38.2	42.7	55.8	5.98	6.69	8.75	0.90	1.01	1.32	0.28	0.32	0.41	33.6	25.8	33.7
3	10.50	37.4	41.8	26.8	29.9	51.4	4.28	4.79	8.22	0.84	0.94	1.61	0.11	0.12	0.21	30.6	22.4	38.5

Table 17: Conversion of exiting results to dry basis and dry, ash-free basis

Key		
ad	air dried, as analysed	To convert to other bases, multiply by the following:
db	dry basis. moisture free	$100/(100 - M_{ad})$
daf	dry, ash-free	$100/(100 – (M_{ad} + A_{ad})$
wt - %	percentage of total mass	

Table 18: Key for different bases and their conversion

Therefore results were compared to existing data using Sample 1, the sample that contains all of the grain-dust matter on either a dry basis or dry, ash-free basis.

Basis type	wt - % db				wt - % daf		
Source	**Measured**	**BIOBIB database**			**Measured**	**Biedermann & Obernberger (2005)**	
Barley type	**Barley grain-dust (Sample 1)**	**Barley - straw**	**Summer barley - straw**	**Winter barley - straw**	**Barley grain-dust (Sample 1)**	**Wheat, rye, barley - straw**	**Wheat, rye, barley - grains**
C	42.81	42.88	46.86	46.79	46.40	49.00	46.00
H	5.46	5.53	5.31	5.53	5.92	6.30	6.60
N	0.84	0.56	0.73	0.41	0.91	0.50	2.00
S	/	0.25	0.12	0.06	/	0.10	0.10
Cl	0.68	0.35	0.98	0.41	0.74	0.40	0.10

Table 19: Comparison of elemental results with existing data

Sample 1, which contained the whole sample of grain-dust, was compared against data from the BIOBIB database and research completed by Biedermann & Obernberger (2005). The variety of barley grown at Highland Grain Ltd is Spring Barley and no exact data was available in regard to this variety, however BIOBIB did contain data for the straw of other barley varieties. The N content of the grain-dust was shown to be higher compared to straw varieties from the BIOBIB database. This correlates with data from Biedermann & Obernberger (2005), existing data shows that grain contains almost 4 times as much N than straw and therefore a higher concentration of N in the sample of grain-dust demonstrates that there is a significant portion of grain in the dust sample. The Cl content however is higher for 4 out of 5 results which raises concerns for grain-dust due to Cl's influence on emissions and HCl formation. This may be due to the type of barley grown or the excessive use of chlorinated fertilizers. Results for C and H were comparable with existing data and showed good correlation.

5.7 Analysis Summary

Sample name		Measured			BIOBIB database			CEN/TS 14961		Fuel Analysis of grain screenings (Jiang et al, 2005)	Units
Parameter	**Basis**	**Sample 1 (all)**	**Sample 2 (<1.0mm)**	**Sample 3 (<0.5mm)**	**Barley - straw**	**Summer barley - straw**	**Winter barley - straw**	**Wheat, rye, barley - straw**	**Wheat, rye, barley - grains**		
Moisture content	**[ad]**	10.50	10.50	10.50	/	/	/	/	/	11.47	**m%**
Ash Content	**[ad]**	6.92	21.10	37.40	/	/	/	/	/	8.27	**m%**
	[db]	7.73	23.57	41.79	4.95	5.88	4.86	5.00	2.00	9.34	**m%**
Carbon	**[db]**	42.81	42.66	29.95	42.88	46.86	46.79	/	/	/	**m%**
	[daf]	46.40	55.82	51.45	/	/	/	49.00	46.00	41.00	**m%**
Hydrogen	**[db]**	5.46	5.37	3.47	5.53	5.31	5.53	/	/	/	**m%**
	[daf]	5.92	7.03	5.97	/	/	/	6.30	6.60	5.60	**m%**
Oxygen	**[db]**	42.47	27.07	23.73	45.48	40.12	41.94	/	/	/	**m%**
	[daf]	46.03	35.42	40.76	/	/	/	43.00	45.00	31.61	**m%**
Nitrogen	**[db]**	0.84	1.01	0.94	0.56	0.73	0.41	/	/	/	**m%**
	[daf]	0.91	1.32	1.61	/	/	/	0.50	2.00	1.83	**m%**
Sulphur	**[db]**	/	/	/	0.25	0.12	0.06	/	/	/	**m%**
	[daf]	/	/	/	/	/	/	0.10	0.10	0.22	**m%**
Chlorine	**[db]**	0.68	0.32	0.12	0.35	0.98	0.41	/	/	/	**m%**
	[daf]	0.74	0.41	0.21	/	/	/	0.40	0.10	/	**m%**
Gross Calorific Value	**[db]**	19.18	17.44	15.63	19.24	18.57	18.78	18.81	18.42	19.74	**MJ/kg**
	[daf]	20.78	22.82	26.86	20.24	19.73	19.74	19.80	18.80	21.77	**MJ/kg**
Net Calorific Value	**[db]**	17.98	16.28	14.88	18.02	17.40	17.56	17.58	17.05	18.52	**MJ/kg**
	[daf]	19.49	21.30	25.56	18.96	18.49	18.46	18.50	17.40	20.43	**MJ/kg**

Table 20: Summary of analysis carried out on samples 1, 2 & 3 and comparison with existing data

6) Dust Burners

6.1 Principles of Solid Biofuel Combustion

As discussed in section 2.4 Chemistry of Combustion, ideal combustion is the complete oxidation of the solid organic part of the fuel into gases CO_2 and H_2O. The conversion process occurs in three steps (Obernberger et al, 2004):

I. Drying – water vaporisation
II. Pyrolysis/gasification – thermal degradation in the absence or presence of externally supplied oxygen
III. Char oxidation - Final oxidation of the charcoal and flue gases

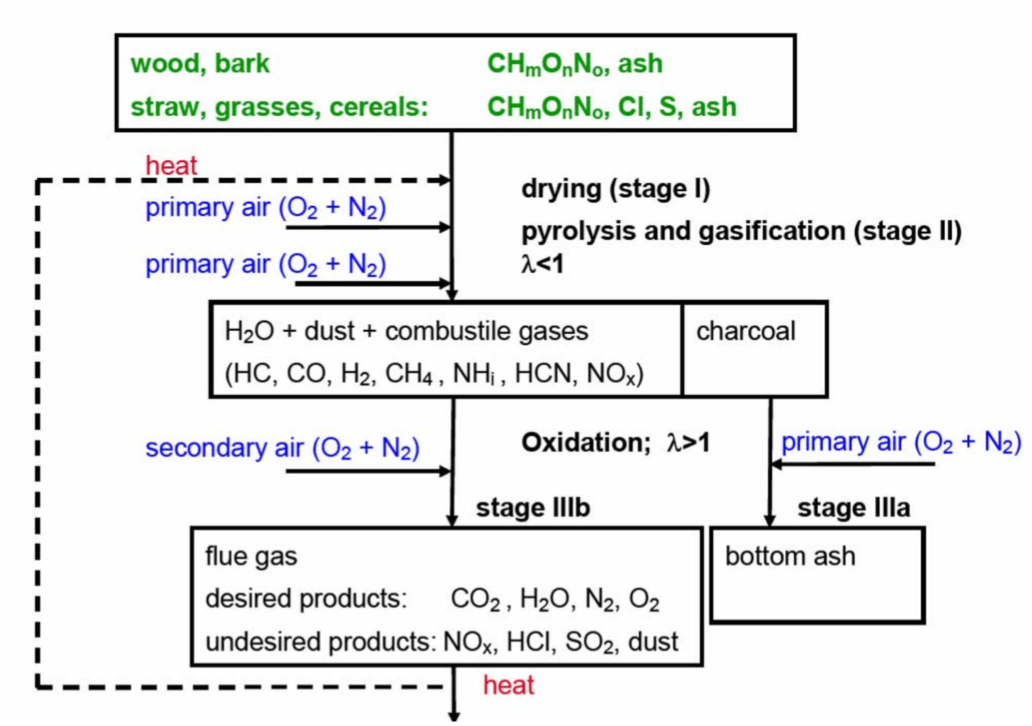


Figure 21: The process of biomass combustion (Obernberger et al, 2004)

The ratio between the amount of air added and the air necessary for complete combustion is the main control parameter of the combustion process and is referred to as lambda (λ, excess air) factor.

When λ is less than 1, incomplete oxidation occurs and not all the fuel is converted into thermal energy. Alternatively when λ>>1, too much air is added that cools the process and leads to incomplete combustion and thermal losses. Ideally, λ should equal 1 for optimum combustion. Realistically this is difficult due to the mixing constraints of the system. Thus in order to achieve complete combustion, a total λ between 1.1-1.8 in large scale and 1.5-2.0 for small scale is common, depending on the technology of the system (Obernberger et al, 2004).

By separating the combustion stages and thus increasing the retention time for reactions, it is possible to lower the total λ. This type of separation can enable optimised control and is referred to as staged combustion. Efficient combustion and low amounts of undesired products depend on the optimisation of each combustion step depending on the technology applied and type of biofuel (Obernberger et al, 2004).

6.1.1 Current Dust Burning Technology

Burns (2002) states that dust burners operate with a suspension of fine combustible particles to produce a flame similar to that of an oil burner. Usually modern dust burners include refinements such as flue gas re-circulation to control emissions such as nitrous oxides.

According to Paulrud (2004), dust (or powder) burners mix fuel and air to produce stable free burning flames and low emissions. Conventional coal dust burners mix the fuel and air very rapidly, and the result is short hot flames and high burnout. However, in order to reduce the NO_x emissions in biomass combustion systems, air staging techniques have been developed. By creating air stages, the mixing of fuel and air is delayed to create a fuel-rich zone close to the burner, and this decreases the conversion of volatile N to NO. The air necessary to complete combustion then enters downstream in the flame. This is referred to as burner air staging or internal air staging (Fig. 22).

An alternative approach is furnace air staging or external air staging where the tertiary air is added just above the burner (Fig. 23).

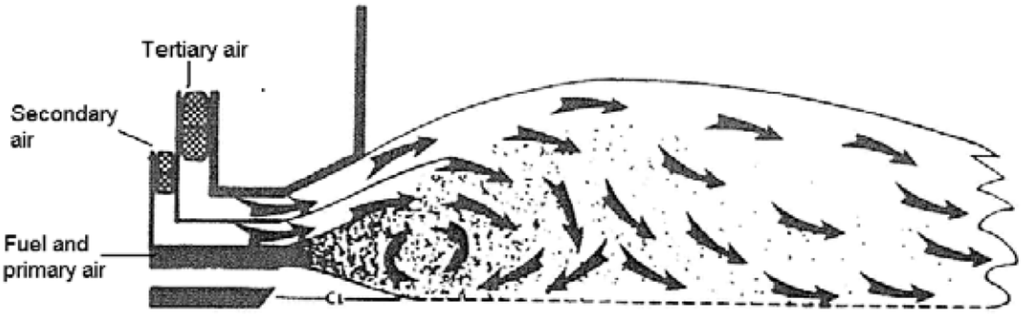


Figure 22: Illustration of burner air staging (Paulrud, 2004)

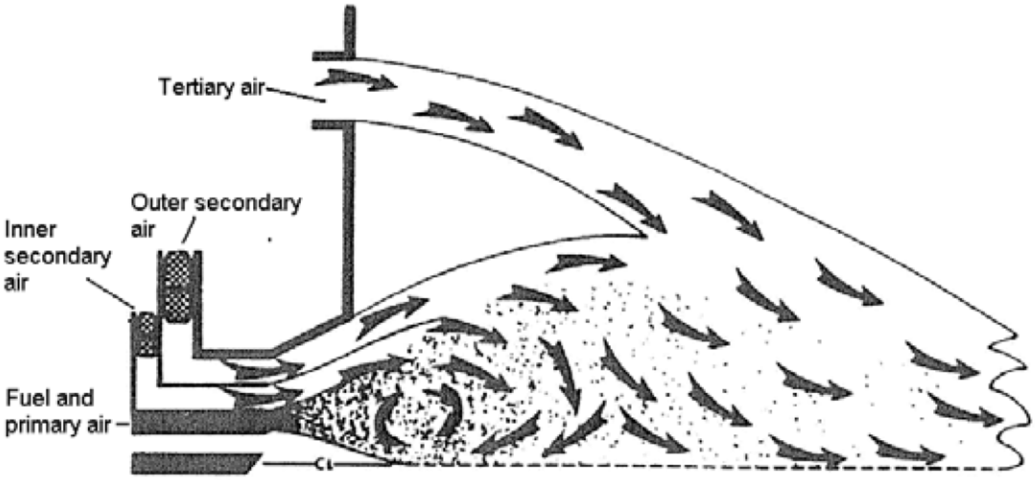


Figure 23: Illustration of burner air staging (Paulrud, 2004)

Unfortunately stable ignition and good burnout is difficult to achieve due to aerodynamics and stoichiometry. However by utilising a swirl principle on the burners, a flame with a strong rotation can be achieved. Flame stability is achieved as the rotation contributes by re-circulating hot combustion gases from down-stream to the burner inlet. The heat is therefore allowed to dry and this ignites the incoming fuel particles. The degree of swirl can be controlled using swirl vanes establish the swirl and by adjusting the vane angle.

According to Paulrud (2004), converting oil-fired or coal-fired boilers into wood dust combustors has been a commercial technology in Sweden for more than 10 years. Specially designed dust burners are retrofitted in existing boilers to burn finely milled wood dust or finely milled pellets.

6.2 Commercial Models

6.2.1 Wood Dust Burners

In Sweden, according to Paulrud (2004), there are two main types of wood dust burners: the VTS burner and a burner from Petrokraft. These burners are low NO_x burners with internal air staging. The main difference between these burners is how the dust is fed to the flame. In addition to the two main models, a Swedish company TPS has recently developed a cyclone-type burner, called BioSwirl, for dust fuels and crushed pellets.

VärmeTeknisk Service (VTS) Burner

In the VTS burner[1], the fuel mixed with air is transported through the centre of the burner and primary, secondary, and tertiary air is inserted through different inlets (Paulrud, 2004).

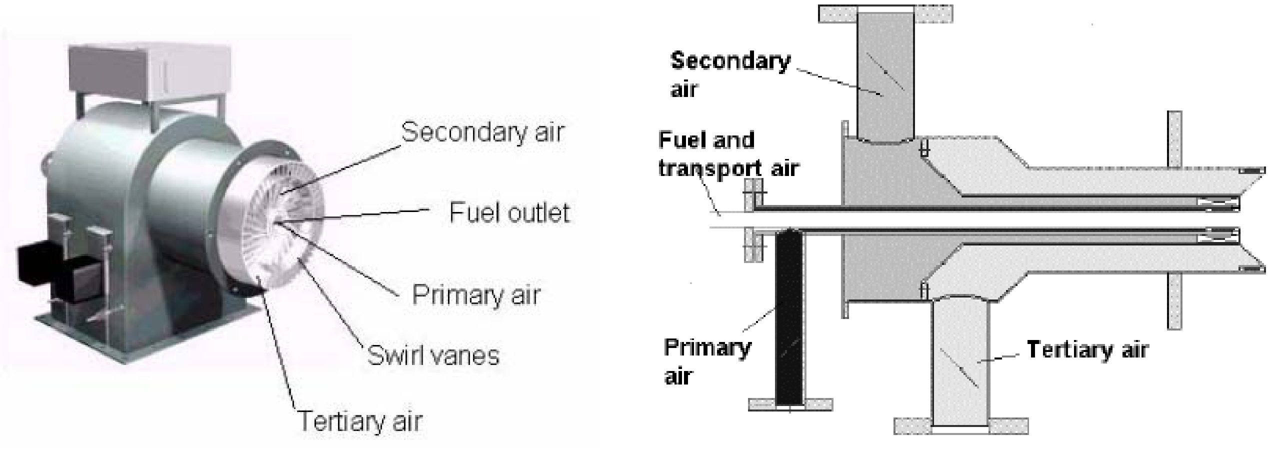


Figure 24: Air distribution and swirl vanes in VTS Dust burner (Paulrud, 2004)

VTS burners consist of a swirl burner where the combustion air is divided into four flows:

- dust transport air
- primary air (high pressure)
- secondary air
- tertiary air

The VTS dust burner is available in different sizes from 500kW-10 MW. The turn-down ratio of the VTS dust burner is 4:1, i.e. a 10MW unit will operate adequately from 10MW down to 2,5MW. This creates a flame very similar to oil firing and allows complete burn out of wood dust in the flame.

The VTS dust burner contains a propane start-up burner that ignites an oil burner; the oil burner is then subsequently used to ignite the dust. Even though the oil burner is for igniting the dust it can also operate solely on oil, in the case of dust shortage. When firing dust the flame is stable and homogeneous over the whole load range and there is no need for pilot fuel.

The dust dosing unit could be placed up to 150 m away from the burner and the dosing of dust is controlled by a frequency controlled motor. The fuel transportation is a ‘dense

---

[1] http://www.vts.nu/products.htm

phase' type, meaning that approx. 1 kg of air transports 3,5kg of dust.

During the combustion the flame is stabilized by high pressure primary air in the swirl generator placed close to the dust outlet. The advantage with this is the possibility to decrease the load of the burner and still keep the flame stable. The VTS dust burner can easily be retrofitted and replace oil burner

Petrokraft Burner

In the PETRO Pulverised Bio Fuel Burner[1], the fuel is inserted outside and there is an oil lance in the centre, surrounded by the air distribution. The demand on the dust quality and feeding equipment is increased using a small combustion unit such as this. In order to produce a stable flame, the feeding must be optimised and even, and the fuel needs to be finely milled with no lumps or splinters (Paulrud, 2004).

The Petrokraft biofuel burners have a range of 6-25 MW depending on the size of burner, with a turn-down ratio of >1:3. The burners currently operate with a combination of fuels:

- Gas/wood.
- Oil/wood.
- Oil/gas/wood.

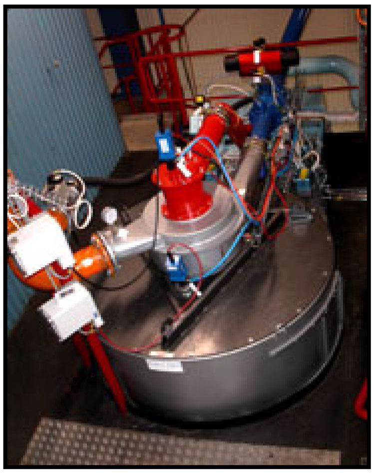


Figure 25: PETRO Pulverised Bio Fuel Burner

These burners have a good burn out of fuel and have low CO and NO_x emissions.

Paulrud (2004) discusses how the effect of burner air staging might be less when using a small burner since the distances between primary, secondary, and tertiary air inlets are too short to have a significant influence on the residence time.

BioSwirl

A Swedish company TPS has recently developed a cyclone-type burner, called BioSwirl[2]. BioSwirl has been developed by TPS for crushed wood pellets and is well suited for conversion of coal and oil-fired furnaces of 0.5 to 25 MW.

---

[1] http://www.petrokraft.se/petrokraft/index.htm

[2] http://www.tps.se/index_en.htm

The dust is pyrolised within a cyclone chamber of the burner forming pyrolysis gas. The gas is then introduced into the furnace section of the boiler through an opening where secondary and tertiary air is added, this allows a controlled gas flame is established in the furnace.

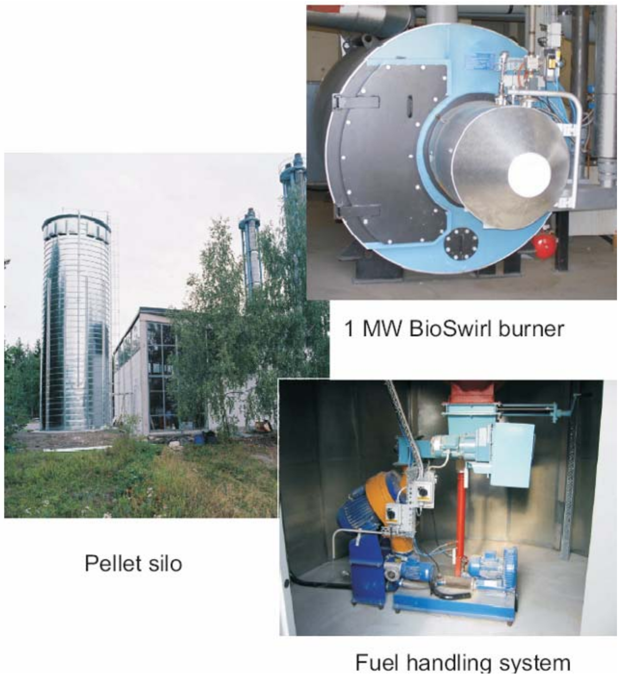


Figure 26: BioSwirl Burner

Some of the advantages of BioSwirl are:

- Support fuel is only necessary during start up or as an alternative fuel
- Low emission of NOx and combustible gases
- Wide control range >1:5 with retained environmental performance
- Free burning, which gives the optimal operating and maintenance cost
- Easily retrofitted
- Insensitive to the composition and particle size
- Suitable for alternative fuels

BioSwirl provides low emissions over a wide load range and permits a high output power per furnace cross-section area.

It is interesting to note that Scottish and Southern Energy (SSE) has recently commissioned TPS to build six new BioSwirl biomass burner systems to be part of the new 300MW biomass burning system at Ferrybridge C power station[1]. Although the system will be commissioned on wood pellets, eventually SSE will be able to utilise other biomass materials such as olive residue from the olive oil industry.

Comment on Wood Burners

Dust burning technology has been in existence for a number of years and therefore is a tried and tested technology. In the case of grain-dust burning, existing wood dust burners could be adapted and modified to burn grain-dust. Allowances would have to be made for ash and

---

[1] http://www.engineeringtalk.com/news/hfa/hfa104.html

slag formation in order to achieve effective and efficient energy conversion. However this modifying or designing a grain-dust burner based on existing wood dust burner is a possibility if biomass burners prove to be inadequate or expensive.

6.2.2 Biofuel Burners

COEN Dual Air Zone Scroll Burner

The Coen DAZ (Dual Air Zone) burner[1] burns pulverised coal, wood fines, and biomass residues using concentric louvered zones that divide the combustion air stream into two counter-rotating streams.

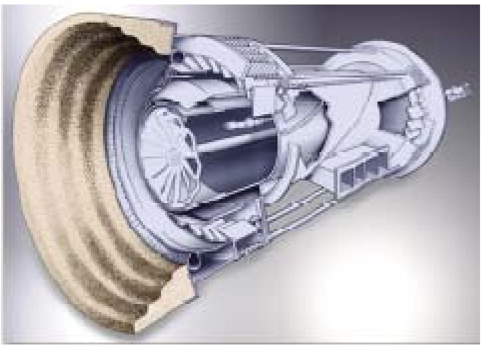


Figure 27: Coen DAZ (Dual Air Zone) Burner

FEATURES

The DAZ burner is multi-fuel system that allows other fuels to be burned in addition to or in combination with the solid biomass fuel. The "Dual Air Zone" with concentric louvers divides the combustion air stream into two counter-rotating concentric streams. The Biomass scroll is designed to allow solid fuels to enter uniformly into an annulus between the two counter-rotating air streams. The air streams scrub against each other providing a turbulent, controllable mixing action with fuels.

The burner has an adjustable flame pattern that is advantageous in fitting industrial furnace configurations, especially tight package boiler furnaces. The DAZ Scroll Burner promotes early ignition, and creates a stable flame for optimal combustion. Combustion originates well back in the throat of the burner allowing a hot refractory flame base to be maintained.

BENEFITS

- Over 5,000 units in operation
- Wide turndown range
- Two adjustable air zones
- Wide variety of possible flame shapes
- Design allows for complete efficient combustion
- Low emission of NO_x

---

[1] http://www.coen.com/i_html/daz.html

COMMENT

This burner has potential for further investigation, however the principle feedstocks listed appear to have a large particle size and therefore whether the burner would cope with grain-dust would need to be examined. In addition, the capacity of the burner to deal with slag formation and ash is unclear. Exact information regarding the burner's capacity and specification were not available in the public domain at the time of writing.

LMB Multifuel Burner (LBE)

LBE is a German company that designs and manufactures Single, Dual and Multifuel Burner[1] for different applications and types of fuel such as:

- asphalt dryer
- hot air generators
- boiler
- lime kilns (annular shaft kilns)
- melting furnaces

Figure 28: LBE Multifuel Burner

LBE is a leading manufacturer of LMB Multifuel Burner with pulverized biofuel being one of the fuels that can be used in the burner.

FEATURES

- Dust firing without support flame
- Multi-fuel design (Gas/Oil/Dust)
- External flue gas recirculation
- Pilot burner with flame safety
- Combustion chamber cooling

---

[1] http://www.lbe-online.de/lbe2002/sonst/LMB_%20D_GB.pdf

- Pneumatic dust conveying
- Preheated air up to 400°C
- Air atomizer for oils

BENEFITS

- Stable, reliable and low polluting combustion
- Great burner turn-down 1:4 to 1:10
- Compact design and economical operation

Thermix Inc. is a specialist combustion company and exclusive Canadian agent of LBE, a German manufacturer of biomass dust burning and conveying equipment. Thermix[1] and its partner company Alternative Green Energy Systems Inc (AGES Inc)[2], jointly market a the LMB Biomass Dust Burner. This burner is part of a series of burners that has been perfected over 20 years to give a safe, efficient, and low polluting combustion system firing wood dust as fuel.

COMMENT

This LMB Multifuel burner has strong potential to be a suitable burner for the desired application. However issues such as ash, deposit formation and burn quality in regard to grain-dust could only be assessed with trials. This option is further discussed at the end of the chapter.

6.2.3 Applicable Technology

KDS Micronex - Biomass Disintegrator

PRINCIPLE OF OPERATION

First American Scientific Corporation (FASC) is an innovative equipment manufacturer and provider of the KDS Micronex[3] system. The basic principle of the system is that kinetic energy is employed to grind and dry a wide variety of raw and recycled materials into extremely fine dust comparable to talcum powder.

---

[1] http://www.thermix.com/biomass-dust-burner.htm

[2] http://www.ages-biomass.com/biomass-dust-burner.htm

[3] http://www.fasc.net/index.htm

"The KDS Micronex operates on the principle of sonic destruction. The internal design of the machine is such that a standing wave is set up. The shape and distribution of this standing wave are controlled by adjustment of the power input and the rotational speed of the KDS Micronex. When material is introduced into this sonic field it resonates. The frequency of resonance is primarily a function of the density and the tensile strength of the material. By tuning the sonic field it is possible to separate materials of different density. In this case, water saturates the ambient air inside the KDS Micronex chamber, and is then removed from the system thus effecting mechanical drying. The material disintegrates into a burnable talcum powder like dust inside the KDS Micronex chamber."

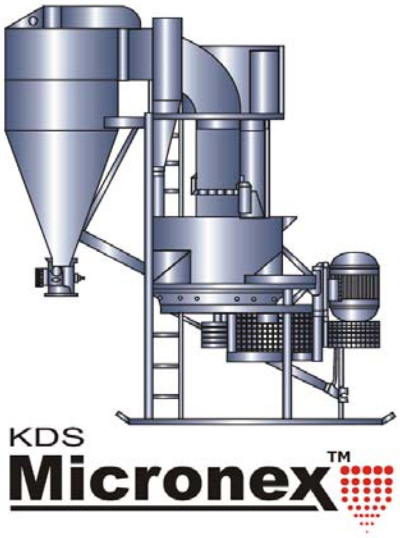


Figure 29: KDS Micronex - Biomass Disintegrator

KEY APPLICATIONS

It is possible to feed a blend of several different industrial and organic materials into the Micronex, and produce a uniformly ground and blended product. Raw feed material of up to 15cm can be reduced to 100µm and finer.

The KDS Micronex claims to be able to handle a huge variety of materials, but most importantly can process biomass waste into fuel and fertilizer; this includes crop residues and grain.

Some burners require a certain moisture content, which could be problematic for grain-dust as the moisture content varies depending on the collection point in the process. Therefore an additional advantage of the KDS Micronex is that it can process materials containing up to 80 % moisture and thus results in significant cost savings by eliminating the need for separate drying equipment.

COST/PERFORMANCE

Although no specific figures are available for the cost of the KDS Micronex, the cost performance and versatility of the KDS Micronex far exceed that of any other equipment being used for similar purposes in the market today. FASC claim that the capital, installation, and operating costs associated with the KDS Micronex are significantly lower than comparable equipment on the market today.

COMMENT

The reason this system has been included in the market analysis, is its potential to solve problems such as particle size, chaff/straw removal, utilisation of seconds and moisture content. If a mixture of grain-dust, chaff/straw and seconds were introduced into the KDS Micronex, they could instantly be reduced to a very fine homogenous dust negating the need for product removal, sieving, grinding or milling.

In addition the moisture content would be reduced to a constant level regardless of the different moisture content present from samples removed at different stages in the process. A particular advantage is that excess straw from harvesting could be used to increase the amount of biofuel feedstock and reduced to powder in the same process and then combusted in the dust burner.

THERMIX Dust Handling System

Thermix Combustion Systems[1] have developed technology to manage and handle dust for biomass combustion. The technology for the accurate control of the dust supply was originally developed for handling pulverised coal.

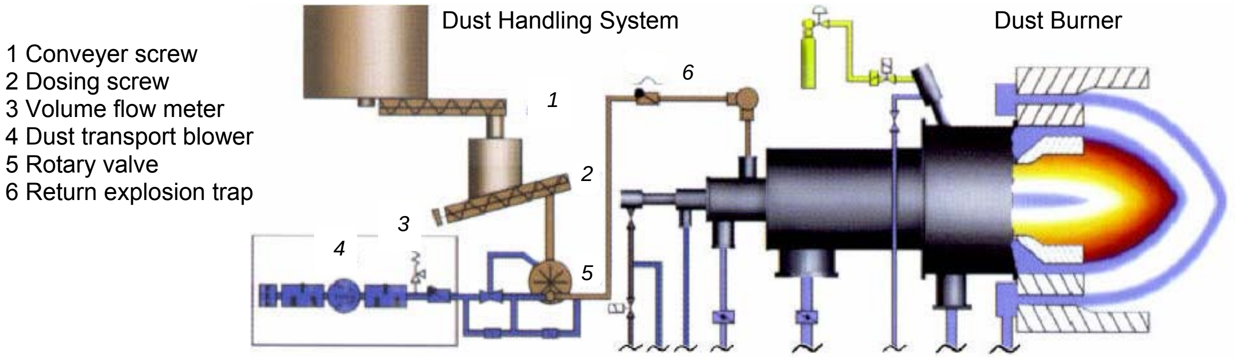


Figure 30: Dust Handling System connected to Dust Burner

PRINCIPLE

"From a storage system, the dust is discharged into a surge silo. Dry air is vented into this chamber to purge saturated air from the discharged dust and the silo is agitated to homogenize the powder which is then conveyed to the top of the burner silo. The burner silo is sized to smooth out variations in the particle distribution.

In operation, dust is transferred to the burner silo via a conveyor. At the base of the silo is a second speed regulated conveyor which delivers the dust to a small dosing hopper

---

[1] http://www.thermix.com/biomass-dust-handling.htm

immediately above the rotary air lock valve. There the dust is discharged into the high-pressure airflow from the compressor. Dust is blown through the system in suspension and emerges at the burner nozzle at a precisely controlled rate."

It is important for biomass burning applications that the O_2 content of the flue gas never falls below 3%. Therefore in the Thermix system, precise dust metering is achieved by a combination of the speed of the regulated feed screw and a rotary air lock valve. The flow of dust is, monitored and controlled at all times during the operation of the burner.

COMMENT

The dust handling system has been included for interest, as it introduces possibilities to solve handling problems and address a method for continuous feedstock supply

6.2.4 Biomass Combustion System

Alternative Green Energy Systems Inc (AGES Inc)[1] is a joint venture licensing consortium between:

- Thermix Inc, a combustion company with dust burning technology, control system and dust handling
- First American Scientific Corporation (FASC), developer of the KDS Micronizer technology
- LBE, company producing Multifuel dust burners

Together these companies have developed a biomass combustion system integrating their various technologies. The Micronizer KDS system reduces most biofuels to a fine dry powder with less than 8% moisture that has excellent combustion properties when used in combination with LBE/Thermix biomass dust suspension burners.

"The new system is a fully integrated solution that incorporates material handling from the biomass reserve, screening and transport, dust preparation, storage and delivery of the dust fuel to the burner."

The FASC patented KDS technology incorporated into the larger AGES KDS3000 dewaters and disintegrates wet biomass waste materials kinetically, without heat, in a process that requires less than ¼ of the energy of conventional drying systems.

---

[1] http://www.ages-biomass.com/biomass-system.htm

The 'KDS dry product' produced from these wet biomass materials is then combusted directly in a Thermix/LBE dust firing system. These dust burners are fired downwards into Thermix designed combustion and segregation chambers which separate the ash/clay and produce clean products of combustion.

The system has a single control panel with safety controls, monitoring system, programmed material handling system and pollution control measures built in. The system can operate with conventional fuels fired alone or in combination thus allowing flexibility regarding changes in fuel prices or biofuel availability.

AGES claim that there is a tremendous potential for substantial fuel cost savings when this technology is applied to substitute a fossil fuel consumer with fuel derived from local biomass waste.

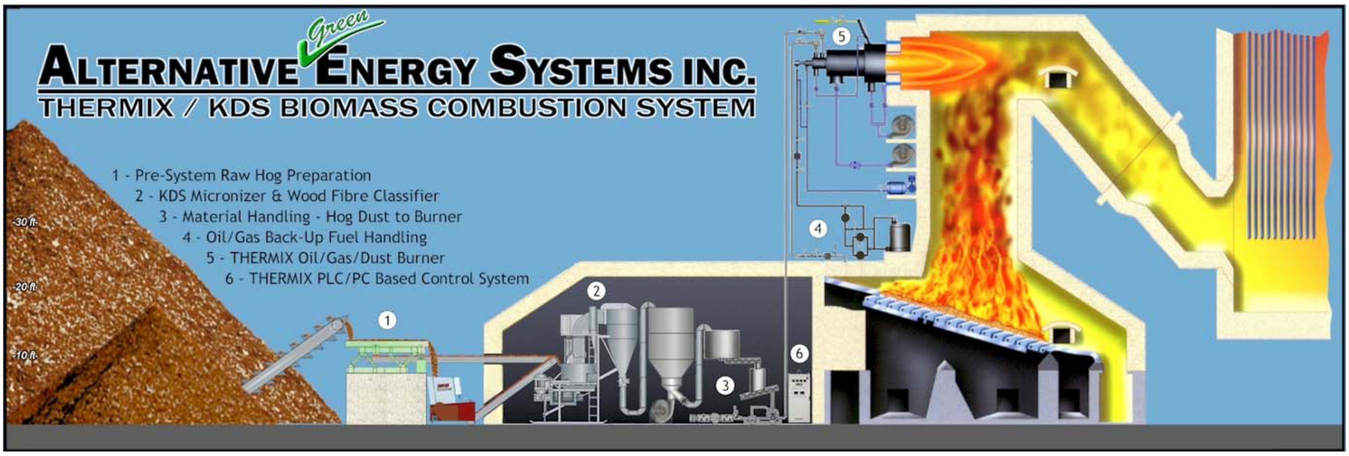


Figure 31: AGES Biomass Combustion System

COMMENT

The combustion system has been included in this section as it introduces new possibilities for energy production from grain-dust on a large scale. The feedstock could be a combination of grain screenings, grain-dust and straw or alternatively when stocks are low sawdust or wood chip could be used. To be cost effective, the system would need to run for the duration of the year and therefore in the summer could be used to provide heat for drying grain and in the winter heat could be sold to the local communities or commercial greenhouses.

6.2.5 Dust Burner Selection

Having identified a number of wood dust burners on the market, a few biomass dust burners were examined. There are only a limited number of dust burners that claim to burn biomass dust and even fewer that list agricultural residues as a feed stock.

Two biomass burners were identified to have the potential to be used as grain-dust burners:

- COEN Dual Air Zone Scroll Burner
- LBE Multifuel Burner (the same as the Thermix Biomass Dust Burner)

Neither burner described grain-dust as a fuel, however similar feed stocks to grain-dust were listed such as whole grain or agricultural residues such as chaff, husk and straw. From the detailed specifications of the LBE Multifuel Burner available in the public domain, it was possible to determine that the burner would likely be a suitable candidate for replacing the fossil fuel burner. Immediate classification of the COEN burner was not possible due to the lack of the burner specifications and capability information.

LBE has had extensive experience in wood dust combustion, the first system was installed over 30 years ago, and since then the technology has undergone continuous refinement to increase its safety standards and reduce its emissions (Bioenergy Update, 2002). LBE technology has been successfully installed worldwide; fuels used include sawdust, shavings, MDF fibre waste, ground construction waste, straw and rice husks. A number of companies were approached for information and LBE was the most responsive company and very helpful in proving further information and assistance. Therefore the LBE dust burner has been selected for further investigation and development, due to the large amount of information immediately available regarding the dust burner and the longevity of LBE’s experience burning biofuels.

7) Design and Integration

7.1 LBE Biomass Dust Burner[1]

Burner Components

1. Dust Inlet
2. Central Gas Inlet
3. Oil Supply/Oil Return
4. Atomizing Air
5. Purging Air
6. Central Air
7. Gas
8. Primary Air
9. Secondary Air
10. Flame Safeguard

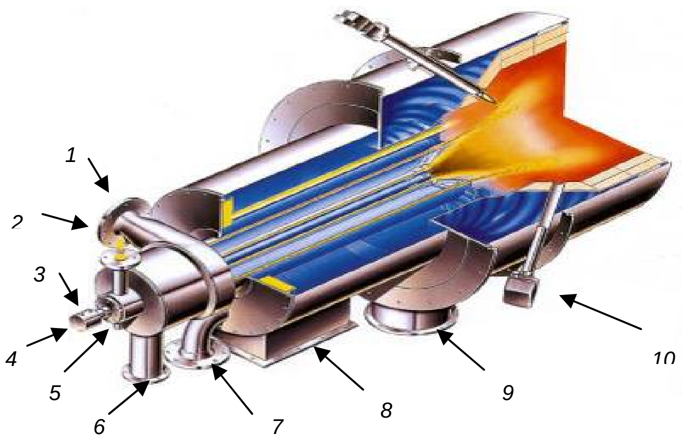


Figure 32: Diagram of LBE biomass dust burner

Dust Burner Principle

"The principle of the design relies on flame stabilisation by spinning the fuel and the primary air supply. The amount of spin is adjustable by changing the position of a spin vane inside the burner. This enables the flame to be shaped to fit the combustion space of the equipment. The support fuel could be any one of a number of support fuels. The support fuels can be used in combination when under the control of the dedicated Thermix controls package.

Fuel gas flows down a central gas tube surrounding the optional oil lance, with the balance of the fuel gas entering the burner through several annular gas lances. Fuel dust is introduced to the burner down the larger of the concentric tubes. The system is designed to ensure that the wood dust is completely removed from the dust injection tube in the event of a disruption of the fuel supply. This burner is capable of operation at 100% dust, providing that the dust is properly prepared.

The burner tile is manufactured from a high duty refractory material and is specifically designed to promote stable combustion. Ports for the pilot burner and the flame detection system enable the burner to be automatically fired with most standard flame detection and

---

[1] http://www.lbe-online.de/lbe2002/sonst/LMB_%20D_GB.pdf

programming systems. The burner tile is cooled by a concentric flow of secondary air. The annular gap between the tile and the burner casing may be used for NOx reduction measures such as flue gas recirculation and for air staging".

Performance Features

Figure 33: Photo of LBE biomass dust burner

- Capacity 3–100 MW
- turndown range 1:5 to 1:8 (1:10 on request)
- Fuels: light fuel oil, heavy fuel oil, burnable gases, wood dust, coal dust, dust from biomass
- Also available as single-fuel burner for light/heavy fuel oil and gas
- Modular construction of burner and components, therefore easy change of wearing parts
- Steady flame at the mixing device
- Staged feeding of combustion air for low flame temperatures
- Dust firing without pilot flame possible
- Preheated combustion air up to 400°C
- Fully automatic burner operation

Key Parts

The key parts of the modular system that need to be considered when installing a dust burner are as follows:

- Burner unit
- Control system
- Gas supply
- Dust supply
- Air supply
- Oil supply
- Injection of additional mediums

The LMB Multifuel Burner, can be operated using oil, gas or dust as a feedstock and are used in unlined hot gas generators and refractory-lined combustion chambers. Due to low ash softening temperatures the refractory lining has to be cooled and so either fresh air or recycled gas is fed through the connection of the windbox and the burner.

7.2 Current Drying System

At Highland Grain, three Cimbria[1] driers are supplied with directly with heat from three 1.0-2MW Weishaupt burners and furnaces.

With the direct heating system, energy is utilised at a much higher efficiency compared to indirect heating system using boilers. There is no loss of heat in the chimney as the flue gas is conducted through the dryer. Although direct heating is the most efficient and effective way of saving energy, there are potential problems associated with burning dust from emissions and ash. Particulates and emissions might affect the quality of the grain as they are released through the dryer in the flue gases, whereas in ordinary circumstances a gas or oil burner would not.

1 Direct heating
2 Hot air chamber
3 Spark Screen
4 Cooling shutter
5 Grain intake
6 Buffer Bin
7 Dryer Column with drying section
8 Volumetric discharge
9 Exhaust chamber
10 Cyclofan
11 Dust waste system

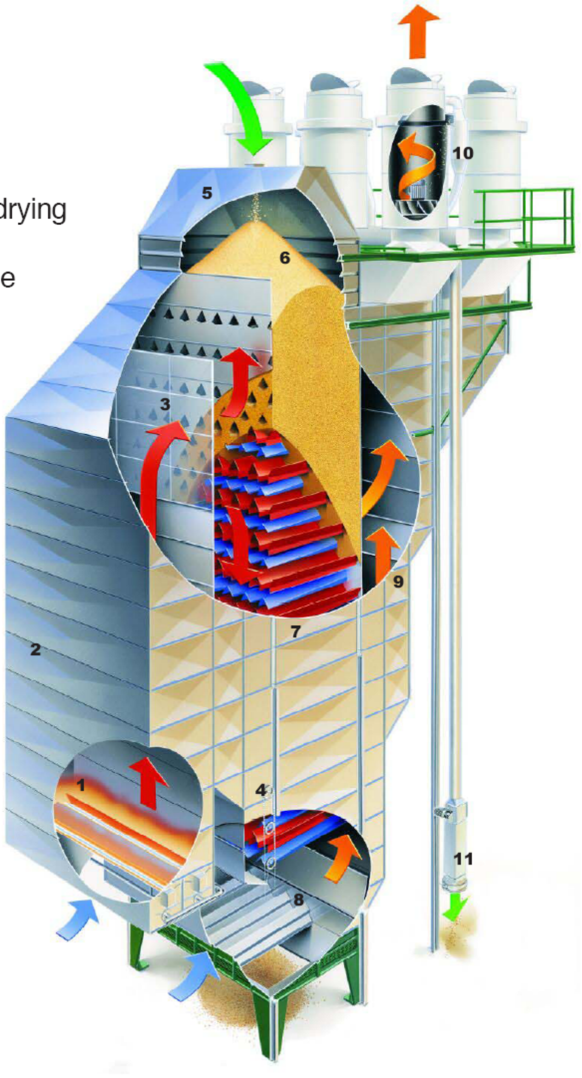


Figure 34: Illustration of an Cimbria Grain Dryer with direct heating (Cimbra Website)

7.2.1 Oil Burners

The burners used in the driers at Highland Grain are Weishaupt[2] Monarch Oil burners, which is one of the best selling units on the market. Weishaupt has been producing Monarch burners for more than 50 years to be used in heat-supply facilities and industrial plants of all types and sizes.

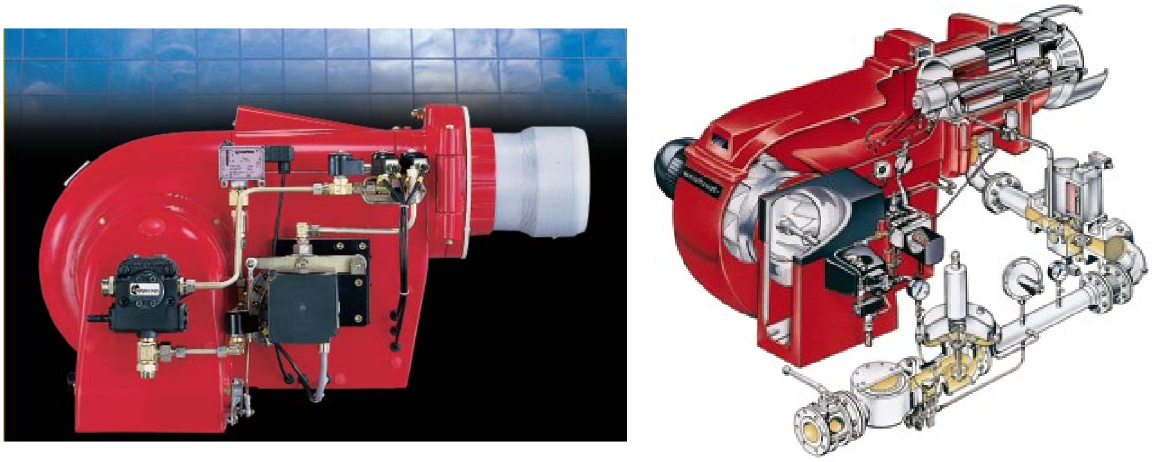


Figure 35: Weishaupt Monarch Oil Burners

The Weishaupt has a mounted oil pump with atomised pressure so no steam or compressed air is required. There is an additional oil solenoid valve for increased safety and a nozzle that has a shut-off valve to prevent oil drips. The fuel ignites using a direct spark. The regulation of oil and air in the burner can be a two-stage, three-stage or modulating system.

In a two-stage system, there is a nozzle head with two nozzles and a motor controlled, quickly opening air damper. In the three-stage system, there are three nozzles and a motor controlled, slowly opening air damper. The burner can be operated in modulating mode by using a suitable controller. Modulating burners are able to operate at any point within the capacity range, depending on the heat demand.

7.2.2 Furnace

The function of the furnace is to deliver an air-mixing system that gives a homogenous drying air temperature. Each Weishaupt oil burner is positioned at one end of the furnace that can be either be installed horizontally or vertically.

The Cimbria furnace consists of a combustion chamber with turbo cone, hot air pipes,

---

[1] http://www.cimbria.com/
[2] http://www.weishaupt-corp.com/products/burners.htm

mixing bend and outer cover. Where the burner is mounted the combustion chamber is clad with ceramic fibre. As the flame of the oil burner burns in the combustion chamber, the heated air and the flue gas is sucked through the hot air pipes and is mixed with the cold air in the mixing bend. By adjusting the spiral openings in the hot air pipes correctly a homogeneous drying air temperature is achieved.

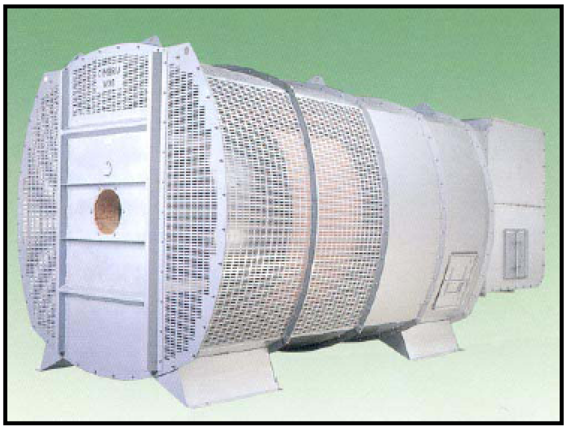


Figure 36: Photo of Cimbria furnace

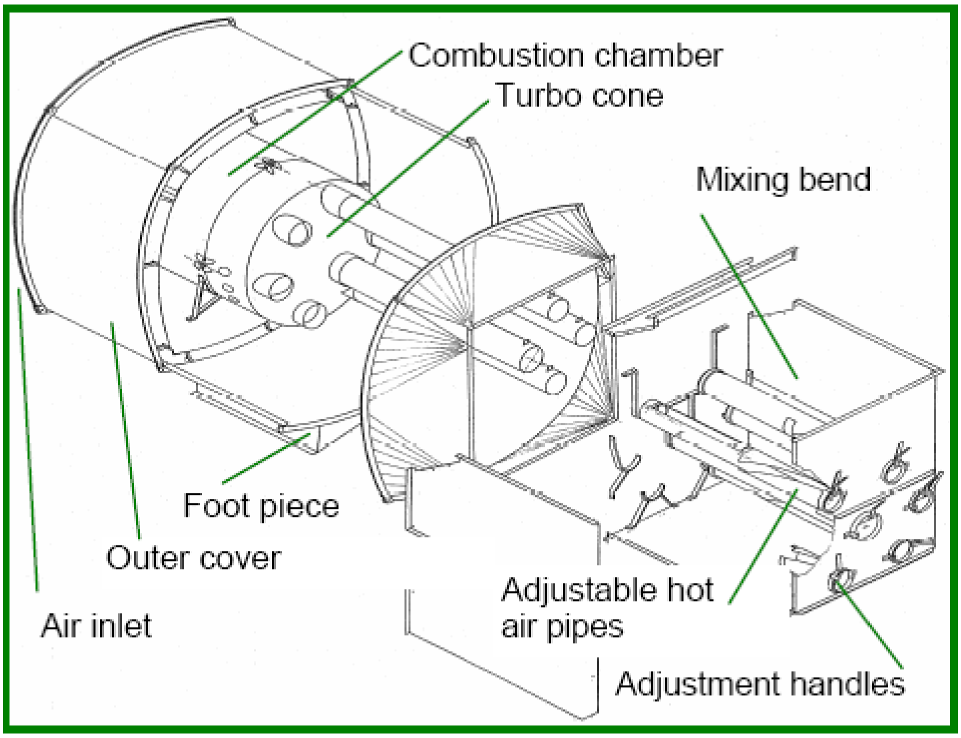


Figure 37: Cimbria furnace sketch

7.3 LBE Grain-dust Analysis

In order to further investigate the possibility of the LBE Multifuel burner, the LBE headquarters in Germany was contacted. Following conversations had with the Manager of Multifuel Burners Division, Ralph Roth, samples of the grain-dust were sent to the LBE. Two samples, 3kgs each, one of grain-dust and one of ‘Seconds’, were sent by Highland Grain to LBE for analysis, testing and feasibility determinations in the dust burners.

7.3.1 Results Comparison

The following table is a summary of the results received from LBE for the 2 samples, grain-dust and ‘seconds’. (The full results are found in Appendices 10.3.7)

Sample name [Basis]		Grain-dust	Seconds	Units
Bulk density		290-320	450-485	kg/m^3
Ignition Point		290	290	°C
Combustion Point		290	290	°C
Ash Softening Point		980	815	°C
Ash Melting Point		1470	/	°C
Humidity/Moisture content	**[ar]**	6.11	6.73	m%
	[ad]	6.12	6.80	m%
Ash Content	**[ar]**	15.55	2.39	m%
	[ad]	15.55	2.39	m%
	[db]	16.56	2.56	m%
Volatile Matter	**[ar]**	66.22	77.69	m%
	[ad]	66.23	77.75	m%
	[daf]	84.54	85.55	m%

Table 21: Summary of LBE results for grain-dust and ‘seconds’

The results received from LBE of the grain-dust and the ‘seconds’ were then compared with the results for Sample 1 that were measured over the course of the project and with results from other sources. Please note that Sample 1 came from EOSF and the samples measured by LBE were from Highland Grain.

The results were converted to either an ‘air-dried’ (ad) basis, a dry basis (db) or a ‘dry, ash-free basis’ (daf), where possible, for comparative analysis. (See Appendices 10.3.1 for conversion methods.)

Sample name		Measured	LBE Results		BIOBIB database			CEN/TS 14961		Analysis of grain screenings Jiang et al (2005)	Units
Parameter	**Basis**	**Sample 1 (all)**	**Grain-dust**	**Seconds**	**Barley - straw**	**Summer barley - straw**	**Winter barley - straw**	**Wheat, rye, barley - straw**	**Wheat, rye, barley - grains**		
Moisture content	**[ad]**	10.50	6.12	6.80	/	/	/	/	/	11.47	**m%**
Ash Content	**[ad]**	6.92	15.55	2.39	/	/	/	/	/	8.27	**m%**
	[db]	7.73	16.56	2.56	4.95	5.88	4.86	5.00	2.00	9.34	**m%**
Carbon	**[db]**	42.81	40.01	42.92	42.88	46.86	46.79	/	/	/	**m%**
	[daf]	46.40	47.94	44.01	/	/	/	49.00	46.00	41.00	**m%**
Hydrogen	**[db]**	5.46	6.41	7.33	5.53	5.31	5.53	6.30	6.60	/	**m%**
	[daf]	5.92	7.68	7.52	/	/	/	/	/	5.60	**m%**
Oxygen	**[db]**	42.47	35.38	45.45	45.48	40.12	41.94	/	/	/	**m%**
	[daf]	46.03	42.40	46.61	/	/	/	/	/	31.61	**m%**
Nitrogen	**[db]**	0.84	1.34	1.52	0.56	0.73	0.41	/	/	/	**m%**
	[daf]	0.91	1.61	1.56	/	/	/	0.50	2.00	1.83	**m%**
Sulphur	**[db]**	/	0.19	0.17	0.25	0.12	0.06	/	/	/	**m%**
	[daf]	/	0.23	0.18	/	/	/	0.10	0.10	0.22	**m%**
Chlorine	**[db]**	0.68	0.11	0.12	0.35	0.98	0.41	/	/	/	**m%**
	[daf]	0.74	0.14	0.12	/	/	/	0.40	0.10	/	**m%**
Gross Calorific Value	**[db]**	19.18	16.42	16.90	19.24	18.57	18.78	18.81	18.42	19.74	**MJ/kg**
	[daf]	20.78	19.67	17.35	20.24	19.73	19.74	19.80	18.80	21.77	**MJ/kg**
Net Calorific Value	**[db]**	17.98	15.67	16.19	18.02	17.40	17.56	17.58	17.05	18.52	**MJ/kg**
	[daf]	19.49	18.79	16.78	18.96	18.49	18.46	18.50	17.40	20.43	**MJ/kg**

Table 22: Comparison of LBE results with measured data and other sources

As can be seen from Table 22, the results from the various sources have good compatibility in most areas; however there are few points that should be highlighted.

- Sample 1 (sourced from EOSF) is much older sample than the samples measured by LBE (sourced from Highland Grain), however it had a higher moisture content as it had been stored in closed packets, as opposed to the LBE sample which had dried out over time
- The LBE grain-dust sample should have a comparable ash content to Sample 1, however it is significantly higher and this is either related to the sampling technique used to obtain the sample or a difference in storage conditions, allowing for more dirt in the higher ash sample.
- The net calorific values on a dry basis show that 'seconds' (grain) has a higher calorific value compared to 'grain-dust' (grain and straw). The net calorific value for Sample 1 is higher than the LBE values because of the high ambient temperature present on the day of measuring the caloric value. In addition the calorific values retrieved by LBE were not experimentally calculated but calculated using formulae based on the chemical composition of the samples.

The results are further discussed in 7.4 Feasibility of Grain-dust Fuel.

7.4 Feasibility of Grain-dust Fuel

In the following section, the feasibility of grain-dust as fuel is practically and economically examined, based on the typical data recommended by LBE compared to the measured data of the grain-dust and 'seconds'.

7.4.1 Fuel Quality

LBE lists the properties of wood dust typically used in their biofuel dust burner. Therefore the values of the grain-dust sample that were measured over the course of the thesis are compared with the wood dust, together with the results from LBE.

ANALYSIS DATA		Typical Wood Dust	Grain-dust (Measured)	Grain-dust (LBE)	Seconds (LBE)
Net Heating value (MJ/kg)	**Dry basis [db]**	18.33	17.98	15.67	16.19
	Normal moisture [ar]	16.5 (10% mc)	15.8 (12%mc)	13.8 (12%mc)	14.2 (12%mc)
Particle Size Distribution	**5.00mm**	/	>100%	>100%	>100%
	1.00mm	>100%	> 70%	> 77%	> 6.2%
	0.50mm	> 98%	> 38%	> 58%	> 3%
	0.315mm	> 50%		> 41%	> 1.2%
	0.250mm	> 25%	> 26%	> 24.3%	> 0.5%
Moisture content %		> 7.0	10.5	6.12	6.8
Ash softening temperature °C		> 1000	/	980	815
Nitrogen content % [db]		< 5.0	0.84	1.34	1.52
Sand/ash content % [db]		< 5.0	7.7	16.56	2.56

Table 23: Fuel requirements for dust burner

Analysis of the data highlights a number of key points:

- The moisture content is likely to be at least 2% higher that wood dust if the feedstock is burnt immediately after processing
- Grain-dust could potentially have a 1-3 MJ/kg difference in energy output (at normal moisture content) compared to wood dust
- The particle distribution of the grain-dust is significantly larger that wood dust, at least 30% of the grain-dust is larger than 1.0mm and for seconds this value is as higher than 90%.
    - This causes problems for dust burning in terms of dust handling, air flow and effective ignition
    - The dust will either need to be milled or sieved

- The ash content of grain-dust is significantly higher than the recommended value for dust burners, 3-12% higher, however for ‘seconds’ i.e. grain it is much lower, almost half, suggesting a high proportion of grain in the grain-dust would be better
- The ash softening temperature for grain-dust is up to 200°C lower than the recommended value and this poses significant problems for slagging and deposit in the dust burner

7.4.2 Fuel Flow-rates

The following comparisons of the flow-rates for different fuels in respect to the capacity of the burners are listed by LBE.

Flow rate (average. values min/max)							
Type	**Capacity**	**Light Oil (kg/h) 42,01 MJ/kg**		**Natural Gas (kg/h) 37,30 MJ/Nm^3**		**Wood Dust (kg/h) 16.74 MJ/kg**	
		Min	**Max**	**Min**	**Max**	**Min**	**Max**
LMB 3	**3,2 MW**	50	260	40	300	130	630
LMB 4	**4,0 MW**	60	340	50	380	165	800
LMB 5	**5,0 MW**	75	420	65	480	205	1000
LMB 6	**6,3 MW**	90	530	80	600	255	1260
LMB 7	**7,1 MW**	105	600	90	680	290	1420
LMB 8	**8,0 MW**	115	680	100	770	325	1600
LMB 10	**10,0 MW**	145	850	125	960	405	2010

Table 24: Flow rates for dust burner

As can be seen from the table a much larger volume of wood dust is required compared to gas or oil; grain-dust is likely to approximate the quantities needed for wood dust with some variation due to a slightly lower calorific value.

7.4.3 Barley Contamination

One of the potential issues, with direct burning using dust is contamination of the barley during drying by ash and particulates. Particulates might affect the quality of the barley which would not be acceptable for malting purposes. Therefore in order to assess the amount of ash that would be in the air drying the barley, the following calculations were completed:

In the Ash section, the following data was given as the average percentage of the different ash fractions to the total amount of ash in ‘straw and cereals’ measured in various test runs at large scale plants (Obernberger et al, 1997).

- *Bottom ash: 80% - 90%*
- *Cyclone fly-ash: 3% - 6%*
- *Filter fly-ash: 5% -10%*

Therefore a maximum ash that could potentially be present would be the sum of the cyclone and filter fly ash, thus 16% of the total ash of the biofuel of the could potentially interfere with the drying of the barley and thus ultimately affect the quality.

- *Using the results of Sample 1, the ash content of the sample was 7.7%*
- *Therefore 16% of 7.7% = 2.72% of the total mass of the sample*

If 3.2MW dust burner was used, a maximum of 630kg/hr and minimum of 130 kg/hr is necessary according to LBE, thus an average of 380kg/hr

- *If 2.72% of 380 kg/hr = 10.336 kg/hr passing through grain, that is 0.172 kg/min and 0.00287 kg/s in three driers.*

This value seems large, however over 80,000m3 of air pass through each drier at Highland grain in an hour, which is 26.5kg/s.

Therefore in each drier:

- *10.336 ÷ 3=3.445kg/hr*
- *And 3.445 ÷ (26.5x3600) = 0.0036 % of the air passing through the drier.*

Consequently although ash is passing through the barley, the ratio of air to ash is so vast that it is unlikely to have any effect on the grain. However it could provide a problem for recirculation in respect to the exaction of dust from the system. Grain-dust is extracted from the process using cyclones and this dust is proposed as a fuel, however ash is now likely to be extracted as well. Therefore ash could potentially contaminate the potential fuel source causing an excessive build up of deposits. Therefore measures will likely be necessary to prevent this.

7.5 Burner Integration

7.5.1 Initial Concepts

Before feasibility and analysis results were received from LBE, it was presumed that two possible options for burner integration at Highland grain existed. As previously mentioned, three Cimbria driers are supplied with heat from three 1.0-2.0MW Weishaupt burners and furnaces at Highland Grain.

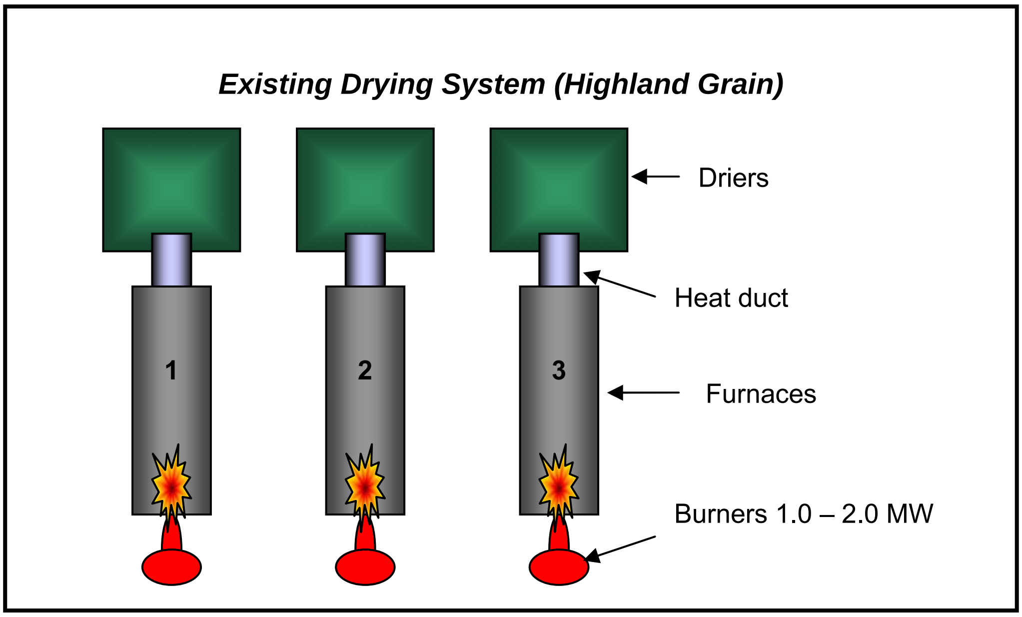


Figure 38: Diagram of existing drying system at Highland Grain

Recently a heat recovery unit was installed at Highland grain and as it recovers 25-35% of the heat in the system the three burners are operating at a much lower power, less than 1 MW. Therefore if a dust burning system was to replace the burners, there are two possible options:

- Replace the three 1.0-2MW Weishaupt burners and furnaces with three 1.0-2MW dust burners
- Replace the three 1.0-2MW Weishaupt burners and furnaces with one 3.2 MW burner

It seems logical to replace the three existing burners with one burner as it would be considerably more economical and more manageable due to cost of three burners compared to a single but higher capacity burner, one feeding system, one control system etc

A 3.2MW burner has almost a four meter long flame, with a one meter diameter, therefore a single burner could be placed perpendicular to the 3 furnaces and feed into each of them.

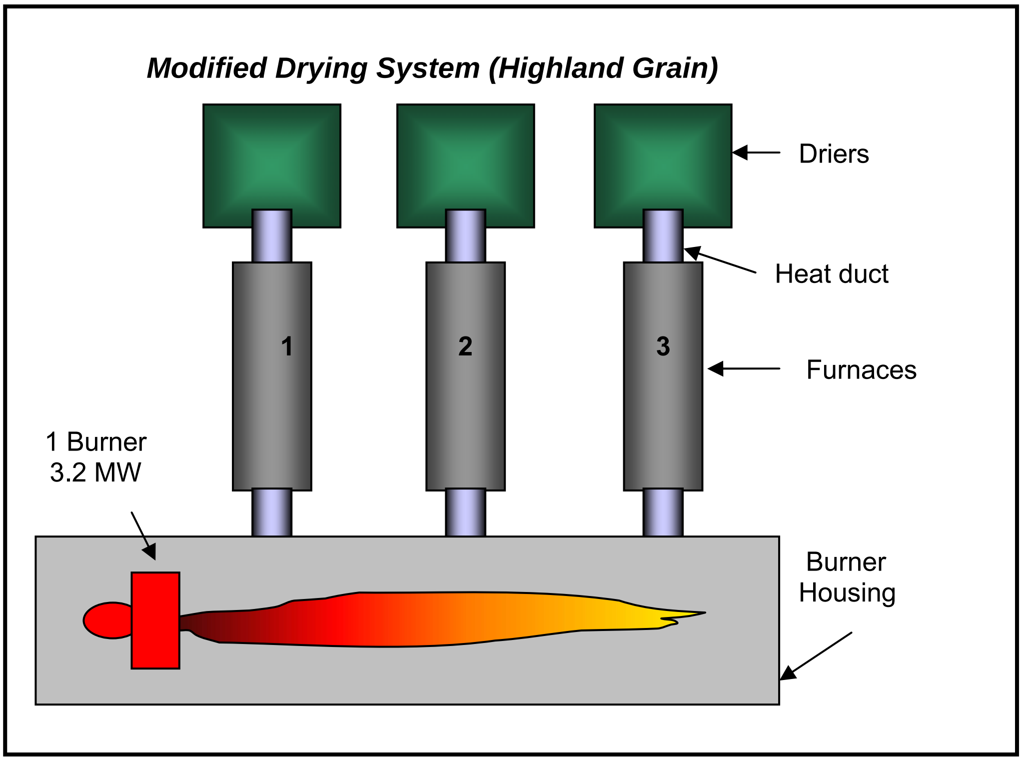


Figure 39: Diagram of modified drying system at Highland Grain

However potential problems might be:

- Uneven distribution of heat between first and third furnace
- Design and material of burner housing
- Heat losses in between burner housing and furnaces

These issues could be solved with an appropriate design of burner housing and ducting to the furnaces however the cost of such an operation and the associated issues might be negated using 3 biofuel burners instead. However the feasibility of this initial integration concept was entirely dependent on the results and analysis of the burner selected and the grain-dust's performance. The results received from LBE meant that this concept was no longer feasible and a different approach would be necessary.

7.5.2 Implications of LBE Results

Results were returned 7 weeks later from the two samples, 3kgs each, one of grain-dust and one of 'Seconds', were sent by Highland Grain to LBE for analysis, testing and feasibility determinations in the dust burners. However, as this was in the concluding stages of the project and an in-depth examination and response therefore was not possible.

The summary of results from LBE and discussion with the Campbell Palmer partnership are as follows:

" LBE stated that both the samples, grain-dust and 'seconds' would need to be milled, as very fine dust is needed, because the firing system uses a substantial amount of gas. In addition, LBE thought it was necessary to mix the 2 fuels. The melting point of both samples is very low, and therefore a cold flame is needed. LBE proposed a vertical burner installation in a big combustion chamber with ash blower and an ash screw at the bottom. The burner will be used to drive a boiler, i.e. a indirect heating method.[1]

The burner would be mounted vertically, with the burner at the top and the flame pointing downwards. Firing downwards would cause a lot of the ash to drop out reducing the amount carried over into flue-ways (if for a boiler solution). This aims to alleviate the problems caused by the low ash melting point of the fuel which will produce a high ash and soot content.

The Highland Grain burners operate, on average at 1.2MW each. The recently installed heat recovery system has reduced to 800kW each. Therefore a 3MW burner with a reasonable turn-down would be a good match for Highland Grain. Operating a burner vertically would enable an even distribution of flame which would be difficult with a horizontal solution. This would also reduce the carry over of ash into the grain dryers[2]*.*

For further development, preliminary sketches are included that detail the burner in a housing to produce hot air (see Appendices 10.5)."

---

[1] Ralph Roth, Manager, LBE Multifuel Burners Division

[2] David Palmer, Director, The Campbell Palmer Partnership Ltd

8) Conclusions and Recommendations

8.1 Summary and Conclusions

The project aim was to investigate the feasibility of whether grain-dust could be burned to provide direct heat in a conventional grain dryer, and therefore replace the traditional diesel fuel source. The key points and conclusions of the project are summarised in the following sections.

8.1.1 Research Summary

Chemical Composition and Related Issues

Research established that in order to design a combustion plant and control system suitable for a particular biofuel, the amounts of elements and effects they cause during combustion must be known.

In order to ascertain the potential properties of grain-dust, which is a mixture of straw and crushed grain; suitable sources of data were found that listed the chemical and physical properties of barley straw and grain separately. This data was used at all stages of the project to compare and contrast with the measured values and identify particular patterns of behaviour in the grain dust.

The main ash forming elements in biofuels are Si, Ca, K, Mg and P. Si combined with K can lead to the formation of low melting silicates in fly-ash particles. Ca and Mg usually increase the ash melting point while K and Na decrease it. A low ash melting point leads to sintering or slag formation in the combustion chamber and this subsequently leads to reduced plant efficiency and lifetime.

As straw, cereal, grass and grain-ashes contain low concentrations of Ca and high concentrations of Si and K, they therefore start to sinter and melt at significantly lower temperatures than wood fuels. Si is often a major element in ash rich fuels, however by itself, silica does not present a problem for biomass boilers due to its high melting point, 1650°C. However, when K is introduced to form K silicates, the melting point of silica-containing material decreases to less than 800°C

Slag formation can be avoided in the burning of grain using a two-stage process; by pyrolising the grain first at a low temperature and then burning the biogas produced in a separate combustion zone at a higher temperature.

A preventative cultivation method for reducing slagging, without interfering with the quality of the barley grain is the application of Cl-free fertilizers, which reduces the amount of chlorine in the barley straw. Cl is a significant factor in deposit formation as it helps to transport the alkali from the fuel to surfaces where the alkali forms sulphates and deposit.

Concentrations of N, S and Cl in different biofuels are of major importance because they cause gaseous emissions such as NO_x, SO_x and HCl. The parameters that affect the formation of these emissions are excess O_2 and CO, furnace temperature and geometry, as well as the dust precipitation systems.

Relevant Technology

Comparable technologies and techniques used to burn other fuels, such as straw are relevant to grain-dust. Deep fluidised beds and cyclone burners were suggested as suitable for straw utilisation. Grain was found to have a much lower content of ash, K, Ca, Si and Cl compared to straw; however it also had a significantly higher content of N. Therefore the tendency for slagging and fouling will be lower for whole crops than for straw, but that the emissions of NO_x from the combustion of grain will be higher.

Upgrading or processing might be necessary if it is not possible to burn the grain-dust due to the varying size of the particles contained within the samples provided. Chaff, husk, and straw are present in the grain-dust samples and this might need to be sieved or milled in order for the sample to be burnt effectively.

8.1.2 Analysis Summary

Limited and varied data exists separately for both straw and grain; however no data concerning the chemical makeup and behaviour of grain-dust was available in the public domain. So analysis on various aspects of the grain-dust was undertaken in the following areas:

Particle size

There were two main reasons for investigating the particle size of the grain-dust sample.

- To establish the particle size distribution of the sample in order to ascertain whether the sample has to be milled or sieved to fulfil equipment recommendations.

- To separate the sample into three different fractions, in order to perform a variety of tests on different types of particle matter.

Analysis showed that in the average sample, 30% of mass is made up of particles larger than 1.0mm, essentially straw, chaff and husk. Whilst 70% of the mass of a sample is grain-dust, particles less than 1.0mm, essentially crushed grain, very small husk/straw and what was latterly determined to be a large amount of dirt.

3 sample sizes were selected for further analysis:

- Sample 1: The whole sample, 30% husk/chaff and a 70% dust
- Sample 2: Any particles smaller than 1.0mm, mixture of dust and fine chaff
- Sample 3: Any particles smaller than 0.415mm, only dust

Calorific values

Net calorific values (NCV) are considered to be a better indication of the "useful energy" available from the fuel, as Gross calorific values (GCV) include the energy required to evaporate the water present in the fuel.

The results were not what were initially expected, Sample 3 was expected to have the lowest calorific values as it had the highest percentage of straw and Sample 1 the highest values, but the inverse true. There was a substantial amount of residue remaining after each test, the amount of which increased significantly through samples 1, 2 and 3. The resulting deposits led to the hypothesis that a large amount of dirt/dust as opposed to grain-dust is present in the two smaller particle samples, samples 2 and 3, explaining the lower calorific values.

The gross calorific value of Sample 1, 19.18 MJ/kg (db), was comparable to existing data which varies significantly, although its value is potentially higher due to the high ambient temperatures at the time of measurement.

Moisture, Ash, C, H, N, O and Cl Content

The moisture content of the grain-dust sample was calculated to be 10.5%, the value was lower than the typical 12% moisture content, but this was expected due to the period of time that the sample had been allowed to dry out.

The ash analysis results showed that Sample 1 had the lowest ash content and Sample 3 had the highest ash content, clarifying the information gained in the calorific tests:

- Sample 1 (all) – 7.7 % wt (db)
- Sample 2 (<1.0mm – 23.6 % wt (db)
- Sample 3 (<0.5mm) – 41.8 % wt (db)

Although all the samples contain dirt which increases the ash content, there is a much higher proportion of dirt to grain product in the smaller samples. However it was interesting to note that the ash content of a sample from which small particles and thus dirt had been removed (1.0mm – 0.4 mm), was only 2.2 % wt (db).

Sample 1, which contained the whole sample of grain-dust, was compared against various data and indicated that higher concentration of N in the sample of grain-dust compared to straw demonstrated that there is a significant portion of grain in the dust sample. The Cl content however is higher for 4 out of 5 results is cause for concern due to Cl's influence on emissions and HCl formation.

Type	NCV (MJ/kg) [db]	GCV (MJ/kg) [db]	% wt [db]						
			Moisture	Ash	C	H	N	Cl	O
Sample 1	17.98	19.18	10.5	7.73	42.8	6.77	0.84	0.68	41.2
Sample 2	16.28	17.44	10.5	23.6	42.7	6.69	1.01	0.32	25.8
Sample 3	14.88	15.63	10.5	41.8	29.9	4.79	0.94	0.12	22.4

Table 25: Summary of analysis results

8.1.3 Design Summary

Dust Burner Selection

A suitable dust burner was selected through careful analysis of the available models. Dust burners operate with a suspension of fine combustible particles; burners mix the fuel and air to produce stable free burning flames and low emissions. Modifying or designing a grain-dust burner based on existing wood dust burner has potential if biomass burners prove to be inadequate or expensive. Therefore 3 types of wood dust burners were investigated: the VTS burner, a burner from Petrokraft and a cyclone-type burner called recently developed by TPS.

Two types of biomass dust burners that were investigated were:

- The Coen DAZ (Dual Air Zone) burner,
- LMB Multifuel Burner produced by LBE

Although neither burner listed grain-dust as a fuel, similar feed-stocks were listed such as whole grain or agricultural residues such as chaff, husk and straw

Other technology available was included such as the KDS Micronex due to its potential to solve problems such as particle size, chaff/straw removal, utilisation of seconds and moisture content.

The LMB Multifuel Burner was selected for further investigation and development, due to the large amount of information immediately available regarding the dust burner and the longevity of LBE's experience burning biofuels.

Key Components and Fuel Requirements

The key components of a dust burner and how combustion could be initiated was established. The burner is available with a capacity of 3–100 MW, and has a turn-down ratio of at least 1:5.

Samples of the grain-dust from Highland Grain were sent to the LBE for analysis and feasibility tests, one of grain-dust and one of 'Seconds'. The analysis of the samples corroborated the earlier analysis and together highlighted a number of key points:

- Grain-dust could potentially have a 1-3 MJ/kg difference in energy output (at normal moisture content) compared to wood dust
- The particle distribution of the grain-dust is significantly larger that wood dust, and will either need to be milled or sieved
- The ash content of grain-dust is significantly higher than the recommended value for dust burners, 3-12% higher, however for 'seconds' i.e. grain it is much lower, suggesting a high proportion of grain in the grain-dust would be suitable
- The ash softening temperature for grain-dust is up to 200°C lower than the recommended value and this poses significant slagging problems in the dust burner

Integration into the Drying System

Using the chosen model, suggestions of how the grain-dust burner would be integrated into a grain dryer were made. At Highland Grain, three Cimbria driers are supplied directly with heat from three 1.0-2MW Weishaupt burners and furnaces.

The project aim was to investigate the feasibility of whether grain-dust could be burned to provide direct heat in a conventional grain dryer, and therefore replace the traditional diesel fuel source. Initially it was hoped that this could be done using a direct heating method as energy is utilised at a much higher efficiency compared to an indirect heating system that utilises a boiler. The three burners are operating at a much lower power, less than 1 MW as a heat recovery unit was recently installed at Highland Grain. Therefore if a dust burning system was to replace the replacing the burners, one 3.2 MW burner could be used to replace the three burners

It was initially thought that a dust burner could be installed perpendicularly to the three furnaces and heat the driers directly. However recent information from LBE indicated that a vertical burner installation in a big combustion chamber, with ash blower and an ash screw at the bottom would be more suitable. The burner will be used to drive a boiler, i.e. an indirect heating method. LBE also stated that it would be necessary to mix and mill the 2 fuels, grain-dust and ‘seconds’, as very fine dust is needed for the dust burners.

8.2 Recommendations

The recommendations and areas for further work can be summarised as follows:

Particle Size

- The mixed particle size of the grain dust needs to be addressed in order to achieve a semi-homogenous sample with a particle size of less than 1.0mm.
    - Either the grain dust needs to be sieved to remove the straw and chaff.
    - Or the grain dust and the 'seconds' could be milled.
- Milling the grain dust and 'seconds' together would increase the amount of feedstock available and reduce the mean ash content of the feedstock.
- Investigations into whether KDS Microionizer, which uses kinetic energy is to grind and dry a wide variety of raw and recycled materials into extremely fine dust, would be a viable option should be undertaken.

Ash and Slag Problems

- Method to prevent, reduce and manage ash and slag should be further investigated.
- The methods should look at cultivation and processing prevention methods as well as ash-management methods.

Dirt

- The problems of dirt in the grain dust and its influence on ash content should be addressed. This can be evaluated from a number of angles:
    - Preventing the dirt from contaminating the grain dust.
    - Removing the dirt from the grain dust.
    - Putting measures in place in the dust burner to deal with the increased amount of ash due to the dirt.

Silicon content

- Considering silicon's implications on slag formation, an area for further research is the actual silicon content of barley grain compared to straw, as no data was found that compared the two simultaneously.

Further analysis on calorific values

- An accurate experiment analysis on both ‘seconds’ and grain dust would be interesting to discover the accuracy of the current values and which value is actually higher as conflicting information exists in this area.

Dealing with emissions

- The emissions from grain dust have not been extensively examined in this project and therefore it is an area for further research for prevention and management techniques.

Indirect/Direct system

- Decisions have to be made as to whether to use an indirect system with a boiler or a direct system.
- If a direct system is to be utilised and a wider selection of burner options should be looked into further.
- However if an indirect system is necessary then alternative technology to dust burning such as fluidised bed and pelletisation should be evaluated.

Vertical burner arrangement

- The main area for further research is whether to take the suggestions of LBE forward and implement their recommended system into the current drying system at Highland Grain
- Quotes for the burner and installation would be necessary to establish whether it is likely to be an economically feasible option.
- Further testing is necessary in addition to computational modelling would be necessary to establish whether it is practically the most efficient and effective method of utilising the grain dust and replacing the oil burners.

9) Sources of Information

9.1 References

- Baxter, L. ; Miles, T.; Miles, T. Jr.; Jenkins, B.; Milne, T.; Dayton, D.; Bryers, R.; Oden, L. (1998) Behaviour of inorganic material in biomass-fired power boilers: Field and laboratory experiences. Source: Fuel Processing Technology, v 54, n 1-3, Mar, 1998, p 47-78
- Biedermann, F. & Obernberger, I. (2005) Ash related problems in biomass combustion plants: Inaugural lecture for the appointment as professor for “Thermochemical Biomass Conversion”. Eindhoven (2005)
- BIOBIB - A Database For Biofuels: Reisinger, K.; Haslinger, C.; Herger, M.; Hofbauer H. Institute of Chemical Engineering, Fuel and Environmental Technology, University of Technology Vienna, Austria
- Boyles, D. (1984) Bio-energy technology, thermodynamics and costs. Publication Details: Chichester Horwood 1984
- Braymo (2005); Heating with Alternative Fuels Presentation, Braymo Energy Corporation, October 11, 2005 Saskatoon.
- Burns, Andrew (Alternative Green Energy Syst. Inc.) Integrated biomass combustion systems Source: Annual Meeting - Technical Section, Canadian Pulp and Paper Association, Preprints, v B, 2002, p B83-B86
- DTi (1999) Energy from Biomass. Summaries of the Biomass Projects carried out as part of the Departments of Trade and Industry’s New and Renewable Energy Programme: Volume 5: Straw, Poultry Litter and Energy Crops as Energy Sources. ETSU BM/04/0056/REP/3
  - Silsoe College, (1985), The Acquisition And Utilisation Of Straw As A Fuel, ETSU B 1115
  - Sheffield Hallam University 1995, Resources Research Unit, School of Urban and Regional Studies, Energy And Carbon Analysis Of Using Straw, ETSU B/M4/00487/01/REP
  - FEC consultants (1988), Straw Firing Of Industrial Boilers, ETSU B 1158
  - Babcock Energy Ltd (1991) Straw Firing Demonstration Trials: Axial Swirl Burner And Fluidised Bed Combustion, ETSU B 1261

  - Babcock Energy Ltd (1993) Straw Ash Characteristics, ETSU B 1242
- DTi (2006) GLOBAL WATCH MISSION Report : Grain – fuel for thought: a scoping mission to Denmark, Published FEBRUARY 2006
- Gough, C.; Schackley, S.; Cannell M. (2002) Evaluating the options for carbon sequestration - Tyndall Centre Technical Report No. 2, November 2002. http://www.tyndall.ac.uk/research/theme2/final_reports/it1_22.pdf (14.4.2005)
- Hytönen J. (2000) ; Use Of Agricultural Plant Based Biomasses And Residues In Energy Production In Scandinavian Area http://www.chem.jyu.fi/ue/frame_left/UEsem2005-Hytonen.pdf
- Jenkins, B.M.; Baxter, L.L.; Miles, T.R. Jr.; Miles, T.R. (1998) Combustion properties of biomass. Source: Fuel Processing Technology, v 54, n 1-3, Mar, 1998, p 17-46
- Jiang, G.; Husseini, G.A.; Baxter, L.L.; Linford, M.R. (2004) Analysis of grain screenings by X-ray photoelectron spectroscopy. Source: Surface Science Spectra, v 11, n 1, Dec. 2004, p 97-104
- Lundberg, H. (2002) Combustion of Crushed Pellets in a Burner. *Abstract of the first world conference on pellets,* Stockholm*,* 2-4 September 2002.
- Maier, D. E., Bakker-Arkema F. W. (2002) Grain Drying Systems, 2002 Facility Design Conference of the Grain Elevator & Processing Society St. Charles, Illinois, U.S.A.
- Mani, S.; Tabil, L. G.; Sokhansanj, S. (2004) Grinding performance and physical properties of wheat and barley straws, corn stover and switchgrass. Source: Biomass and Bioenergy, v 27, n 4, October, 2004, p 339-352
- Miles, T. R.; Miles, T. R. Jr.; Baxter, L. L.; Bryers, R. W.; Jenkins, Bryan M.; Oden, L. L. (1996) Boiler deposits from firing biomass fuels. Source: Biomass and Bioenergy, v 10, n 2-3, 1996, p 125-138
- Obernberger, I (1998) Decentralized biomass combustion: State of the art and future development Source: Biomass and Bioenergy, v 14, n 1, 1998, p 33-56
- Obernberger, I; Biedermann, F; Widmann, W; Riedl, Rudolf. (1997) Concentrations of inorganic elements in biomass fuels and recovery in the different ash fractions. Source: Biomass and Bioenergy, v 12, n 3, 1997, p 211-224
- Obernberger, I.; Brunner, T.; Bärnthaler, T. (2004): Chemical properties of solid biofuels – significance and impact. Source: Standardisation of Solid Biofuels.

- Obernberger, I.; Thek, G. (2004) Physical characterisation and chemical composition of densified biomass fuels with regard to their combustion behaviour. Source: Biomass and Bioenergy, v 27, n 6, December, 2004, p 653-669
- Parker, C.; Roberts, T. (1985) Energy from Waste: An Evaluation of Conversion Technologies / edited by Colin Parker and Tim Roberts. Publication Details: London; New York: Elsevier Applied Science Publishers, Cl985.
- Paulrud, S. (2004) Upgraded Biofuels - Effects of Quality on Processing, Handling Characteristics, Combustion and Ash Melting, Printed by: SLU, Grafiska Enheten, Umeå 2004
- Paulrud, S. ; Mattsson, J. E.; Nilsson, C. (2002). Particle and handling characteristics of wood fuel powder: Effects of different mills. Source: Fuel Processing Technology, v 76, n 1, Apr 20, 2002, p 23-39
- Paulrud, S.; Nilsson, C. (2004). The effects of particle characteristics on emissions from burning wood fuel powder. Source: Fuel, v 83, n 7-8, May, 2004, p 813-821
- Rawle, A. (2001) The Basic Principles of Particle Size Analysis. Malvern Instruments, Malvern, UK, http://www.malvern.se/laboratory/psintro.htm (2001).
- Rice, B; Wedemann, M.; (2005) Cereals as a Fuel. Irish Farmers' Journal 28th May 2005
- Sander, Bo (1997) Properties of Danish biofuels and the requirements for power production (ELSAMPROJEKT A/S) Source: Biomass and Bioenergy, v 12, n 3, 1997, p 177-183
- Skrifvars, B.J., Backman, R., Hupa, M. 1998. Characterization of the sintering tendency of ten biomass ashes in FBC conditions by a laboratory test and by phase equilibrium calculations. *Fuel Processing Technology 56*, 55-67.
- Van loo, S.; Koppejan, J; (2002) Handbook of biomass combustion and co-firing. ISBN 9036517737 Enschede, Netherlands: Twente University Press; 2002.
- Zevenhoven-Onderwater, M. (2003) Ash forming matter in biomass fuels. Åbo Akademi, Finland, Academic dissertation, report 01-03.

9.2 Background Reading

- Abbott, R.; Quick, R. (1990) Utilization of Grain Wastes as a Supplemental Boiler Fuel. Description of A Test Burn At Thunder Bay TGS Source: Symposium Papers - Energy from Biomass and Wastes, 1990, p 607-654
- Bärnthaler, G.; Haraldsson, C.; Zischka, M. Obernberger, I. (2004) Determination of major and minor element contents in solid biofuels. Source: Standardisation of Solid Biofuels. (2004) S. 245-257
- Brunner, T.; Obernberger, I.; Brouwers, J.; Preveden, Z. (1998): Efficient and Economic Dust Separation from Flue Gas by the Rotational Particle Separator as an Innovative Technology for Biomass Combustion and Gasification Plants. 10th European Bioenergy Conference. (1998)
- Copeland B. J.; Davis B. R. (2004) Guide to Safety and Health in Feed and Grain Mills, N.C. Department of Labour, Division of Occupational Safety and Health North Carolina
- De Bruyn Kops, S. M.; Malte, P. C. (2004) Simulation and Modelling of Wood Dust Combustion in Cyclone Burners. Energy and Environmental Combustion Laboratory, University of Washington. Prepared for: U. S. Department of Energy January 30, 2004
- EC Product Directives, Standards & Technical Regulations, Equipment and Protective Systems intended for use in Potentially Explosive Atmospheres (ATEX) Directive 94/9/EC http://ec.europa.eu/enterprise/atex/qa.htm
- EPA (2003) Grain Elevators and Grain Processing Plants, U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Emission Factors and Inventory Group, April 2003
- Frandsen, F. J. (2005) Utilizing biomass and waste for power production - A decade of contributing to the understanding, interpretation and analysis of deposits and corrosion products. Source: Fuel, v 84, n 10, July, 2005, p 1277-1294
- Hays, M. D.; Fine, P. M.; Geron, C. D.; Kleeman, M. J.; Gullett, B. K. (2005) Open burning of agricultural biomass: Physical and chemical properties of particle-phase emissions. Source: Atmospheric Environment, v 39, n 36, November, 2005, p 6747-6764

- Kaufmann, H. (1997) Chlorine-Compounds in Emissions and Residues from the Combustion of Herbaceous Biomass. A dissertation submitted to the Swiss Federal Institute of Technology Zurich
- Krause, U.; Kasch, T. (2000) Influence of flow and turbulence on flame propagation through dust-air mixtures. Source: Journal of Loss Prevention in the Process Industries, v 13, n 3, May, 2000, p 291-298
- Liu, Y.-Z. Yuan, Y.-C.; Chen, Z.-H. (2002) On the combustion mechanism and development of the distillers' grain-fired boiler, Source: Applied Thermal Engineering, v 22, n 3, March, 2002, p 349-353
- M.A.P.C. de Feber, D.J. Gielen (2000) Biomass for Greenhouse Gas Emission Reduction, ECN report C-99-078, IEA OCED
- Munck, l. (1991) advances in barley quality, experiences and perspectives. CIHEAM, 1991. p. 9-18: 1 ill. 2 plates. 8 graphs. 6 tables. Denmark
- Olsson, M. (2006) Wheat straw and peat for fuel pellets-organic compounds from combustion. Source: Biomass and Bioenergy, v 30, n 6, June, 2006, p 555-564
- The Warren Group, Grain Dust Handling part I: Explosion Hazards http://www.warren-group.com/articles/grainpartII.html and Grain Dust Handling Part II: Storage Facilities http://www.warren-group.com/articles/grainpartII.html
- Thy, P.; Jenkins, B. M.; Lesher, C. E.; Grundvig, S. (2006) Compositional constraints on slag formation and potassium volatilization from rice straw blended wood fuel. Source: Fuel Processing Technology, v 87, n 5, May, 2006, p 383-408
- Thy, P.; Jenkins, B. M.; Lesher, C. E.; Williams R.B. (2004) Slag Formation and Potassium Volatilization from Rice Straw Blended Wood Fuel. Prepr. Pap.-Am. Chem. Soc., Div. Fuel Chem. 2004, 49 (1), 89
- Van den Broek, R; Faaij, A.; van Wijk, A. (1996) Biomass combustion for power generation. Source: Biomass and Bioenergy, v 11, n 4, 1996, p 271-281
- Weissinger, A.; Fleckl, T.; Obernberger, I. (2000) Investigations on the Release of Nitrogen Compounds from the Fuel Bed in Grate Furnaces. Source: 1st World Conference on Biomass for Energy and Industry, Vol. 2. (2000) S. 1792-1733
- Xiuzhi, S. S. (2005) Overview of Plant Polymers: Resources, Demands, and Sustainability. Published by Elsevier

9.3 Standards

These standards are entitled Draft for Development and are Technical Specification (CEN/TS) was approved by CEN. It is being issued in the Draft for Development series of publications and is of a provisional nature because the new edition of the international document has been issued as a Technical Specification and is open to further development. It should be applied on this provisional basis, so that information and experience of its practical application may be obtained.

After two years the members of CEN will be requested to submit their comments, particularly on the question whether the CEN/TS can be converted into a European Standard.

Although these standards are locate on the BSI (http://www.bsonline.bsi-global.com) these publications are not to be regarded as a British Standard.

- DD CEN/TS 14774-1:2004 Solid biofuels. Methods for the determination of moisture content. Oven dry method. Total moisture. Reference method
- DD CEN/TS 14774-2:2004 Solid biofuels. Methods for the determination of moisture content. Oven dry method. Total moisture. Simplified method
- DD CEN/TS 14774-3:2004 Solid biofuels. Methods for the determination of moisture content. Oven dry method. Moisture in general analysis sample
- DD CEN/TS 14588:2004 Solid biofuels. Terminology, definitions and descriptions
- DD CEN/TS 14918:2005 Solid biofuels. Method for the determination of calorific value
- DD CEN/TS 14961:2005 Solid biofuels. Fuel specifications and classes
- DD CEN/TS 14775:2004 Solid biofuels. Method for the determination of ash content
- DD CEN/TS 15103:2005 Solid biofuels. Methods for the determination of bulk density
- DD CEN/TS 15104:2005 Solid biofuels. Determination of total content of carbon, hydrogen and nitrogen. Instrumental methods
- DD CEN/TS 15105:2005 Solid biofuels. Methods for determination of the water soluble content of chloride, sodium and K
- DD CEN/TS 15148:2005 Solid biofuels. Method for the determination of the content of volatile matter

- DD CEN/TS 15149-1:2006 Solid biofuels. Methods for the determination of particle size distribution. Oscillating screen method using sieve apertures of 3,15 mm and above
- DD CEN/TS 15149-2:2006 Solid biofuels. Methods for the determination of particle size distribution. Vibrating screen method using sieve apertures of 3,15 mm and below
- DD CEN/TS 15149-3:2006 Solid biofuels. Methods for the determination of particle size distribution. Rotary screen method
- DD CEN/TS 15289:2006 Solid biofuels. Determination of total content of S and Cl
- DD CEN/TS 15290:2006 Solid biofuels. Determination of major elements
- DD CEN/TS 15296:2006 Solid biofuels. Calculation of analyses to different bases
- DD CEN/TS 15297:2006 Solid biofuels. Determination of minor elements

10) Appendices

10.1 Original Brief and Deliverables

Background

In the whiskey industry, barley grain is dried to be used either as feed grain or malting barley. Grain dryers traditionally use direct-fired oil burners to heat air to between 60°C and 100°C for grain drying. However, grain drying organisations produce large quantities of fine grain dust during their drying operation which is usually sent to landfill sites. However, the dust has a high calorific value and is combustible and therefore can used as fuel.

A grain dust burner could be potentially be used to replace the traditional 1MW/2MW oil burners that are used to dry the grain and thus reduce fuel costs by more than half.

Aim

The project aim is to investigate the feasibility of whether grain dust can be burned directly in an integrated system in a conventional grain dryer, therefore replacing the traditional diesel fuel source.

Objectives

The objectives of the project can be broken up into the following sections:

iv) Research
v) Analysis
vi) Design and integration

RESEARCH

The following areas will be covered in the research section:

- To establish whether grain dust burning has been done before and whether any relevant patents exist. In addition, comparable technologies and techniques used to burn coal dust for coal boilers saw dust etc. can be identified.
- To establish the key issues associated with the direct burning of dust. This includes a detailed examination of the safety measures and regulations (94/4/EC) required to avoid dust explosions. Crossovers with the flour/sawdust industry can also be looked into.

- To ascertain the potential effects and magnitude of slag formations due to the silica content of the grain dust.

ANALYSIS

The following areas will be covered in the analysis section:

- To establish experimentally the size of dust particle necessary for a complete process
- To calculate calorific values of the dust particles and the effect of moisture vapour on that value
- To determine the chemistry of the combustion of grain dust
- To calculate the dust flow rates/throughputs necessary to match the power generated by the oil burners
- To calculate and determine whether a continuous fossil fuel pilot flame would be required

DESIGN AND INTEGRATION

The following areas will be covered in the Design and Integration section:

- Establish the key components of a dust burner and how combustion could be initiated
- Using current technology, adapt or design a grain dust burner that could be integrated into a grain dryer
- Detail how the burner would be integrated into current grain dryers and discuss implications and issues
- Make recommendations how the design could be taken further through prototyping and manufacturing

Calculate the potential cost savings and pay back periods for successful grain burner/drying integration

10.2 Chemical Data

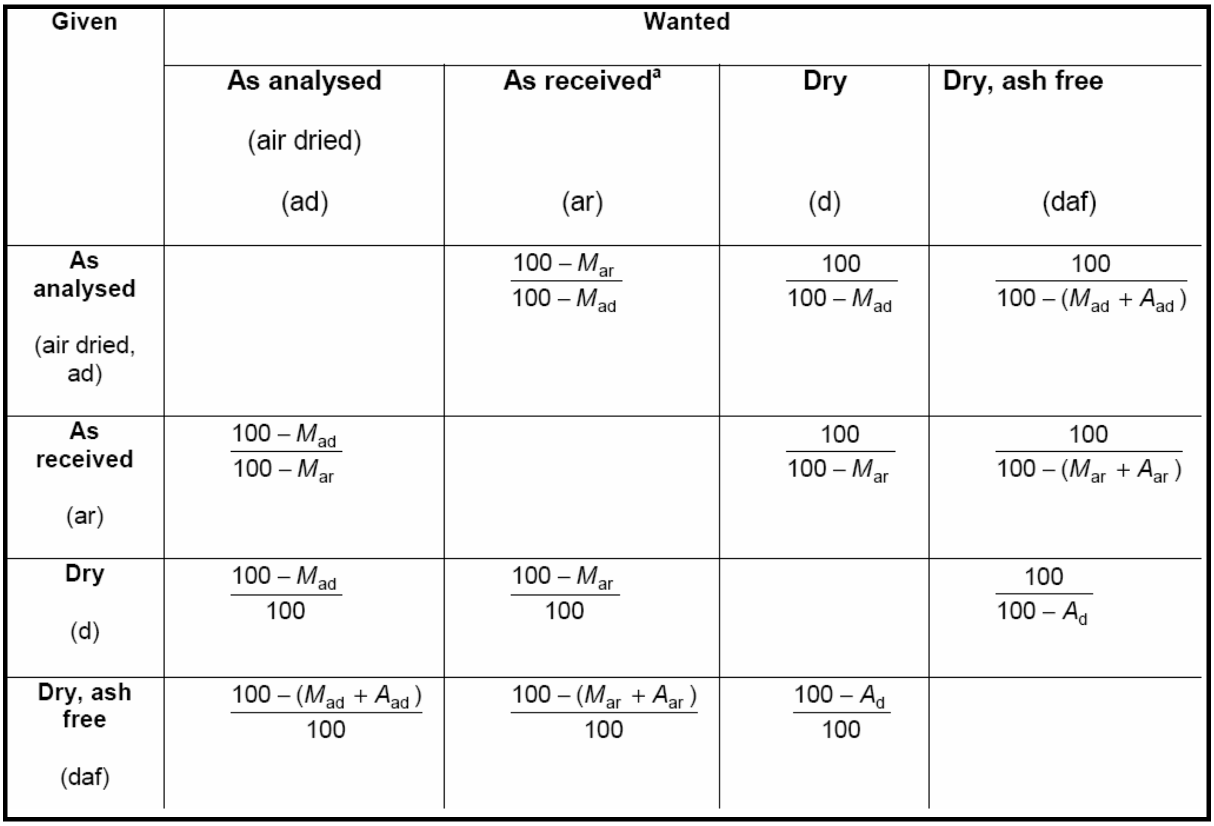
Data extracted from the BIOBIB website: http://www.vt.tuwien.ac.at/Biobib/grass.html

Data from BIOBIB			
Classification	**barley - straw**	**summer barley- straw**	**winter barley - straw**
calorific value			
gross:	19235 kJ/kg	18568 kJ/kg	18780 kJ/kg
net:		17400 kJ/kg	17563 kJ/kg
elementary analysis			
C:	42.88 wt.%,dm	46.86 wt.%,dm	46.79 wt.%,dm
H:	5.53 wt.%,dm	5.31 wt.%,dm	5.53 wt.%,dm
N:	0.56 wt.%,dm	0.73 wt.%,dm	0.41 wt.%,dm
S:	0.25 wt.%,dm	0.12 wt.%,dm	0.06 wt.%,dm
Cl:	0.35 wt.%,dm	0.98 wt.%,dm	0.41 wt.%,dm
O:	**by difference**		
ash content			
a:	4.95 wt.%,dm	5.88 wt.%,dm	4.86 wt.%,dm
ash analysis			
CO_2:	0.40 wt.%	2.50 wt.%	0.59 wt.%
SO_3:	2.53 wt.%	4.43 wt.%	0.91 wt.%
Cl:	8.20 wt.%	11.90 wt.%	2.25 wt.%
P_2O_5:	3.77 wt.%	2.73 wt.%	1.22 wt.%
SiO_2:	51.92 wt.%	33.80 wt.%	59.40 wt.%
Fe_2O_3:	0.14 wt.%..	0.28 wt.%	0.22 wt.%
Al_2O_3:	0.16 wt.%	0.28 wt.%	0.38 wt.%
CaO:	8.06 wt.%	8.30 wt.%	5.10 wt.%
MgO:	1.76 wt.%..	2.22 wt.%	0.77 wt.%
Na_2O:	0.95 wt.%	4.11 wt.%	0.26 wt.%
K_2O:	18.46 wt.%	26.10 wt.%	5.60 wt.%
TiO_2:	0.07 wt.%		
thermal ash behaviour			
SIT: beginning of sintering		720 °C	900 °C
SOT: beginning of softening		760 °C	1000 °C
HT: hemispheric point		1010 °C	1110 °C
FT: flowing point		1080 °C	1180 °C

10.3 Analysis

10.3.1 Formulae for Conversion between Different Bases

Extracted from: CEN/TS 15296 Solid Biofuels - Calculation of analyses to different bases



Given	Wanted			
	As analysed (air dried) (ad)	**As received**[a] (ar)	**Dry** (d)	**Dry, ash free** (daf)
As analysed (air dried, ad)		$\frac{100 - M_{ar}}{100 - M_{ad}}$	$\frac{100}{100 - M_{ad}}$	$\frac{100}{100 - (M_{ad} + A_{ad})}$
As received (ar)	$\frac{100 - M_{ad}}{100 - M_{ar}}$		$\frac{100}{100 - M_{ar}}$	$\frac{100}{100 - (M_{ar} + A_{ar})}$
Dry (d)	$\frac{100 - M_{ad}}{100}$	$\frac{100 - M_{ar}}{100}$		$\frac{100}{100 - A_{d}}$
Dry, ash free (daf)	$\frac{100 - (M_{ad} + A_{ad})}{100}$	$\frac{100 - (M_{ar} + A_{ar})}{100}$	$\frac{100 - A_{d}}{100}$	

10.3.2 Particle Size Distribution

Sieve name	Fraction (mm)	Mass of fraction in sample (g)					Total mass of fractions (g)	Average mass of fraction (g)	% of fraction (based on total mass)
		Sample 1	Sample 2	Sample 3	Sample 4	Sample 5			
1st Sieve(4.0mm)	above 4.0	0.54	0.67	0.69	0.67	0.36	2.93	0.59	3.73
2nd Sieve(2.0mm)	2.0-4.0	0.87	1.07	0.87	1.03	0.69	4.53	0.91	5.76
3rd Sieve(1.0mm)	1.0-2.0	8.31	6.80	4.05	3.00	2.77	24.93	4.99	31.71
4th Sieve(0.415mm)	0.415-1.0	3.54	3.61	5.18	5.14	5.07	22.54	4.51	28.67
5th Sieve(0.25mm)	0.25-0.415	0.66	1.21	1.85	1.74	1.94	7.40	1.48	9.41
Collecting pan	below 0.25	1.64	2.46	3.09	4.13	4.98	16.30	3.26	20.73
Total mass of all fractions		15.56	15.82	15.73	15.71	15.81	78.63	15.73	100.00

10.3.3 Elemental Analysis

	particle size	C	H	N	Cl
Sample 1	all	39.36	6.06	0.87	0.61
	all	39.03	6.34	0.55	0.61
	all	36.56	5.78	0.84	0.61
Average		38.32	6.06	0.75	0.61
Sample 2	>1.0mm	38.61	6.14	0.84	0.31
	>1.0mm	38.73	5.95	0.95	0.28
	>1.0mm	37.21	5.86	0.91	0.26
Average		38.18	5.98	0.90	0.28
Sample 3	>0.5mm	29.07	4.71	0.85	0.12
	>0.5mm	26.38	4.17	0.82	0.10
	>0.5mm	24.96	3.97	0.85	0.11
Average		26.80	4.28	0.84	0.11

10.3.4 Conversion between Gross and Net Calorific Values

Extracted from: CEN/TS 14918:2005 Solid Biofuels - Method for the determination of calorific value

Net calorific value at constant pressure for a **dry sample** (dry basis, in dry matter):

$$q_{p,\mathrm{net,d}} = q_{V,\mathrm{gr,d}} + 6{,}15 \times w(\mathrm{H})_\mathrm{d} - 0{,}8 \times \left[w(\mathrm{O})_\mathrm{d} + w(\mathrm{N})_\mathrm{d}\right] - 218{,}3 \times w(\mathrm{H})_\mathrm{d}$$

$$= q_{V,\mathrm{gr,d}} - 212{,}2 \times w(\mathrm{H})_\mathrm{d} - 0{,}8 \times \left[w(\mathrm{O})_\mathrm{d} + w(\mathrm{N})_\mathrm{d}\right]$$

Net calorific value at constant pressure at a **required moisture content** M (e.g. as received, M_ar, whereupon the symbol of calorific value is $q_{p,\mathrm{net,ar}}$) is calculated:

$$q_{p,\mathrm{net,m}} = \left\{q_{V,\mathrm{gr,d}} - 212 w(\mathrm{H})_\mathrm{d} - 0{,}8\left[w(\mathrm{O})_\mathrm{d} + w(\mathrm{N})_\mathrm{d}\right]\right\} \times (1 - 0{,}01M) - 24{,}43M$$

$$= q_{p,\mathrm{net,d}} \times (1 - 0{,}01M) - 24{,}43 \times M$$

where

$q_{p,\mathrm{net,m}}$	is the net calorific value at constant pressure, in joules per gram, of the biofuel with moisture content M; (usually as received M_ar);
$q_{V,\mathrm{gr,d}}$	is the gross calorific value at constant volume, in joules per gram, of the moisture-free fuel (see 10.4);

10.3.5 Complete Results for Calorific Values

Test	Sample	Mass [g]								Temperature [□C]			Heat released (Q = mq_{gr}) [MJ]			Gross Calorific Value (q_{gr}) [MJ/kg]	
		Pellet (m_p)	Benzoic acid (m_b)	biofuel (m_f)	Wire (m_{w1})	Cotton (m_x)	Wire (m_{w2})	Wire m_{w1}-m_{w2}	Deposit	T_1	T_2	ΔT	Wire (Q_w)	Cotton (Q_x)	b/acid (Q_b)	as received (q_{gr})	dry basis ($q_{gr,db}$)
Calibration		1.196	/	/	0.010	0.076	0.008	0.002	/	22.17	25.22	3.05	0.003	1.330	/	26.452	/
1	1	1.505	/	/	0.009	0.073	0.002	0.007	ash	21.38	23.84	2.46	0.010	1.278	/	16.814	18.786
	2	1.152	/	/	0.013	0.077	0.010	0.003	ash	21.72	23.43	1.71	0.004	1.348	/	14.872	16.617
	3	1.763	/	/	0.013	0.079	0.011	0.002	ash	21.88	24.23	2.35	0.003	1.383	/	13.623	15.221
2 with b/acid	1	1.373	0.130	1.243	0.013	0.075	0.012	0.001	0.120	22.55	25.38	2.83	0.001	1.313	3.439	20.787	23.226
	2	1.407	0.130	1.277	0.010	0.077	0.007	0.003	0.265	23.40	25.94	2.54	0.004	1.348	3.439	17.749	19.832
	3	1.393	0.130	1.263	0.008	0.077	0.006	0.002	0.501	23.13	25.32	2.19	0.003	1.348	3.439	14.952	16.706
3	1	1.270	/	/	0.012	0.076	0.009	0.003	0.138	22.81	24.95	2.14	0.004	1.330	/	17.164	19.178
	2	1.274	/	/	0.012	0.074	0.008	0.004	0.271	22.52	24.48	1.96	0.006	1.295	/	15.609	17.441
	3	1.285	/	/	0.011	0.078	0.008	0.003	0.526	21.72	23.51	1.79	0.004	1.365	/	13.992	15.634

10.3.6 Net Calorific and Gross Calorific values

Source	Sample Type	Gross Calorific Value [MJ/kg db]	Net Calorific Value [MJ/kg db]
MEASURED	Sample 1 (entire sample)	19.178	17.985
	Sample 2 (< 1.0mm)	17.441	16.278
	Sample 3 (< 0.5mm)	15.634	14.877
BIOBIB	Barley/Straw	19.235	18.025
	Summer Barley/Straw	18.568	17.400
	Winter Barley/Straw	18.780	17.563
CEN/TS 14961	Wheat, rye & barley grain	18.424	17.575
	Wheat, rye & barley straw	18.810	17.052
Jiang et al (2005)	Grain screenings	19.736	18.521

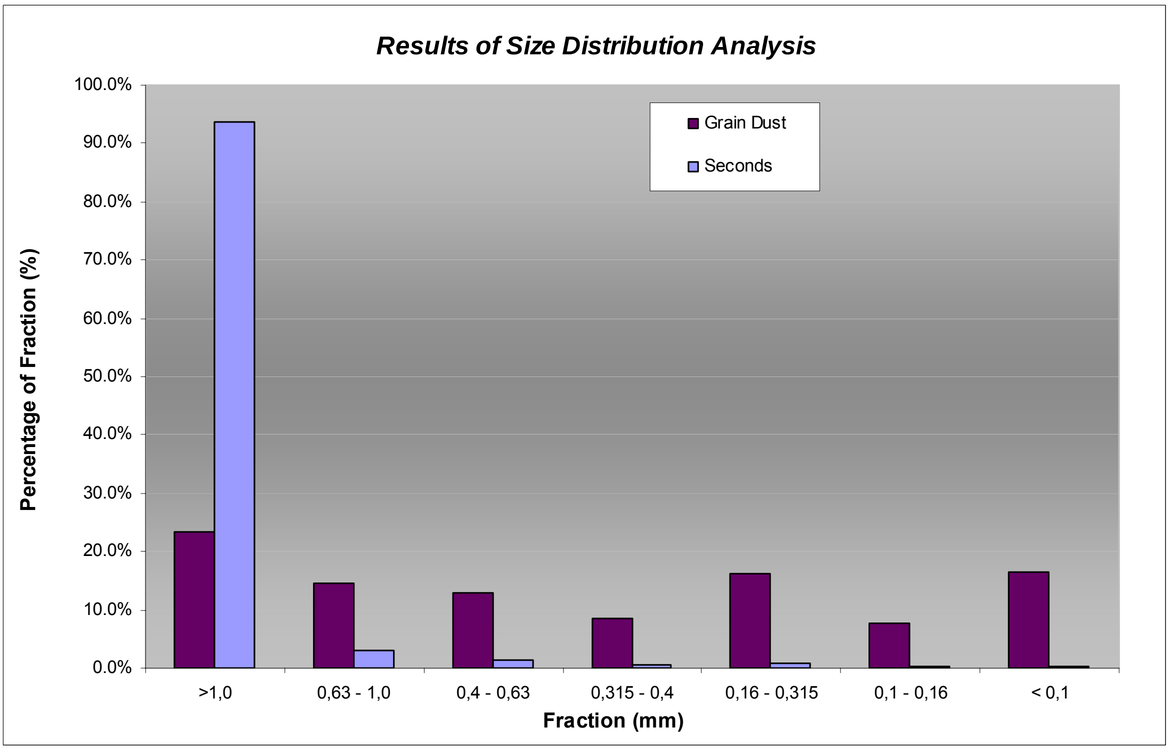
10.3.7 Complete results from LBE

Sample name [basis]		Grain Dust	Seconds	Units	Standards
Bulk density		290-320	450-485	kg/m3	DIN 51705
Ignition Point		290	290	°C	
Combustion Point		290	290	°C	
Ash Softening Point		980	815	°C	DIN 51730
Ash Melting Point		1470	/	°C	DIN 51730
Humidity/Moisture content	[ar]	6.11	6.73	m%	DIN 51719
	[ad]	6.12	6.80	m%	
Ash Content	[ar]	15.55	2.39	m%	DIN 51719
	[ad]	15.55	2.39	m%	
	[db]	16.56	2.56	m%	
Volatile Matter	[ar]	66.22	77.69	m%	DIN 51720
	[ad]	66.23	77.75	m%	
	[daf]	84.54	85.55	m%	
Carbon	[ar]	37.56	39.97	m%	
	[ad]	37.56	40.00	m%	
	[db]	40.01	42.92	m%	
	[daf]	47.94	44.01	m%	
Hydrogen	[ar]	6.02	6.82	m%	
	[ad]	6.02	6.83	m%	
	[db]	6.41	7.33	m%	
	[daf]	7.68	7.52	m%	
Oxygen	[ar]	33.21	42.32	m%	
	[ad]	33.21	42.36	m%	
	[db]	35.38	45.45	m%	
	[daf]	42.40	46.61	m%	
Nitrogen	[ar]	1.26	1.42	m%	
	[ad]	1.26	1.42	m%	
	[db]	1.34	1.52	m%	
	[daf]	1.61	1.56	m%	
Sulphur	[ar]	0.18	0.16	m%	
	[ad]	0.18	0.16	m%	DIN 51724
	[db]	0.19	0.17	m%	
	[daf]	0.23	0.18	m%	
Chlorine	[ar]	0.11	0.11	m%	
	[ad]	0.11	0.11	m%	
	[db]	0.11	0.12	m%	
	[daf]	0.14	0.12	m%	
Gross calorific value	[ar]	15.41	15.74	MJ/kg	
	[ad]	15.41	15.75	MJ/kg	
	[db]	16.42	16.90	MJ/kg	
	[daf]	19.67	17.33	MJ/kg	
Net Calorific Value	[ar]	14.71	15.07	MJ/kg	
	[ad]	14.72	15.08	MJ/kg	
	[db]	15.67	16.19	MJ/kg	
	[daf]	18.97	16.78	MJ/kg	

Please note that LBE did not provide any data on a dry basis (db) except for the values for ash and chlorine, all data in the table listed on a dry basis has been calculated from the values given under a 'air-dried'(ad), 'as received'(ar) and 'dry-ash free'(daf) basis.

10.3.8 LBE Particle Distribution

Sample	**Grain Dust**		**Seconds**	
Fraction	**Mass**	**% of total mass**	**Mass**	**% of total mass**
>1,0	10.00	23.3%	63.60	93.8%
0,63 - 1,0	6.30	14.7%	2.10	3.1%
0,4 - 0,63	5.50	12.8%	1.00	1.5%
0,315 - 0,4	3.70	8.6%	0.30	0.4%
0,16 - 0,315	7.00	16.3%	0.50	0.7%
0,1 - 0,16	3.30	7.7%	0.10	0.1%
< 0,1	7.10	16.6%	0.20	0.3%
Total	42.90	100.0%	67.80	100.0%



10.4 Relevant Patents

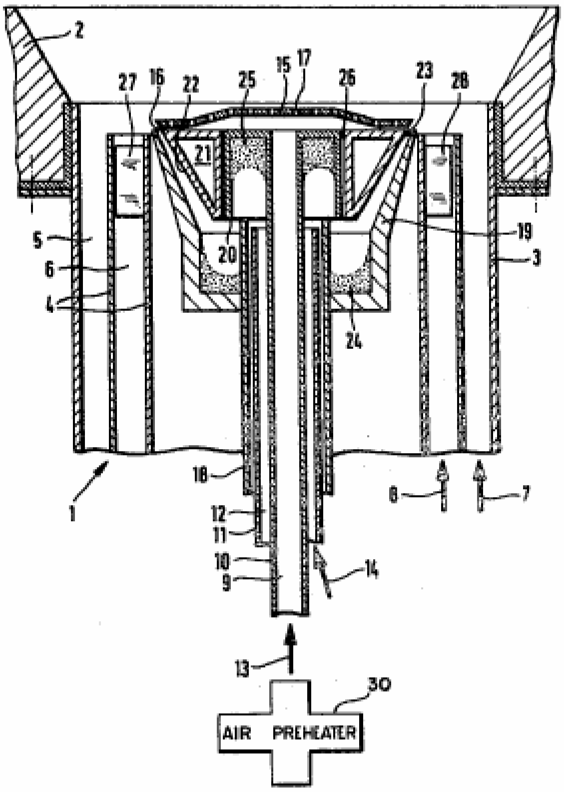
A large number of patents were examined at the start of the project that had links to the coal, cement dust, wood dust industry. However as it became clear that utilising or modifying an exiting model was likely to be the final outcome of the project, intellectual property and patent infringement was no longer an issue.

However the following two patents have been extracted from the European Patent Office[1] and thought to be the most relevant to grain-dust burning.

10.4.1 US4457695

Burner for the combustion of powdery fuels

A burner (1,29) for the combustion of powdery fuels, in particular coal-dust, comprises a central duct (9,37) to supply a jet of core-air (13,41), a fuel channel (12,40) to supply the fuel and a casing channel (5,6; 31) to supply secondary air (7,8; 36). In order to make such a burner (1,29) also suitable for lesser power ranges, a widened range of regulation and less sensitive to a wide coal-dust band, the discharge means of the fuel channel (12,40) is designed as an annular nozzle (23,53) of which at least one of the two circumferential walls (19,47) is rotatable and driven, and the discharge means of the central duct (13,41) being so designed that the jet of core-air (13,41) is directed at least in part outwardly against the discharging fuel for the purpose of deflection into the region of the secondary air (7,8; 36).

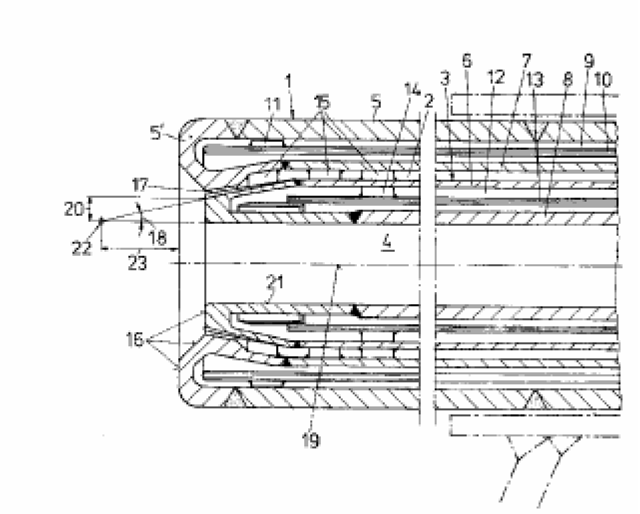


---

[1] http://ep.espacenet.com/

10.4.2 US5127346

BURNER ARRANGEMENT FOR THE COMBUSTION OF FINE-GRAINED TO DUSTY SOLID FUEL



A burner for the combustion of fine-grained to dusty solid fuels incorporates a central internal tube for supplying the solid fuels and an annular gap surrounding the internal tube and delimited by a cooled external tube, for supplying oxygen or oxygen-containing gas. The annular gap ends externally by an exhaust port directed obliquely relative to the longitudinal axis of the burner and peripherally surrounding the end of the central internal tube, or by a plurality of exhaust ports annularly disposed about the longitudinal axis of the burner. In order to ensure the complete combustion of the fine-grained to dusty fuels at a long service life of the burner, the inclination of the exhaust port(s) relative to the longitudinal axis of the burner is below 20 DEG . The exhaust port(s) is/are arranged transverse to the longitudinal axis of the burner and in the radial direction relative to the same at a distance of between 5 and 30 mm from the inner wall of the internal tube. The inclination of the exhaust port(s) relative to the longitudinal axis of the burner and the radial distance of the exhaust port(s) relative to the inner wall of the central internal tube are coordinated in a manner that the intersection of the extensions of the exhaust port and of the inner wall of the internal tube outside of the burner lies 20 to 80 mm in front of the burner mouth.

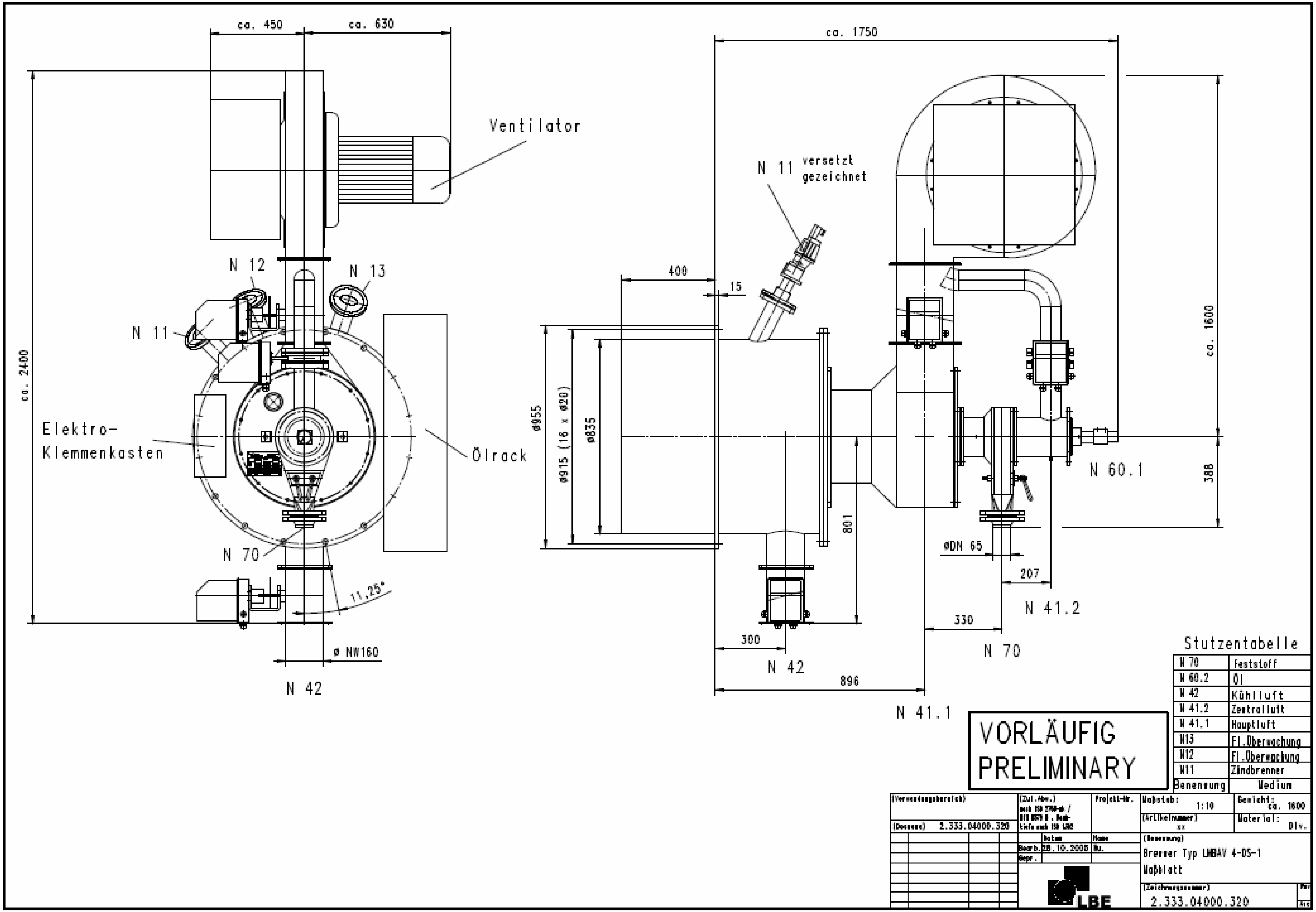
10.5 Design

10.5.1 Drawings from LBE

2 drawings were given as examples by LBE:

1) A 4 MW Oil Dust burner

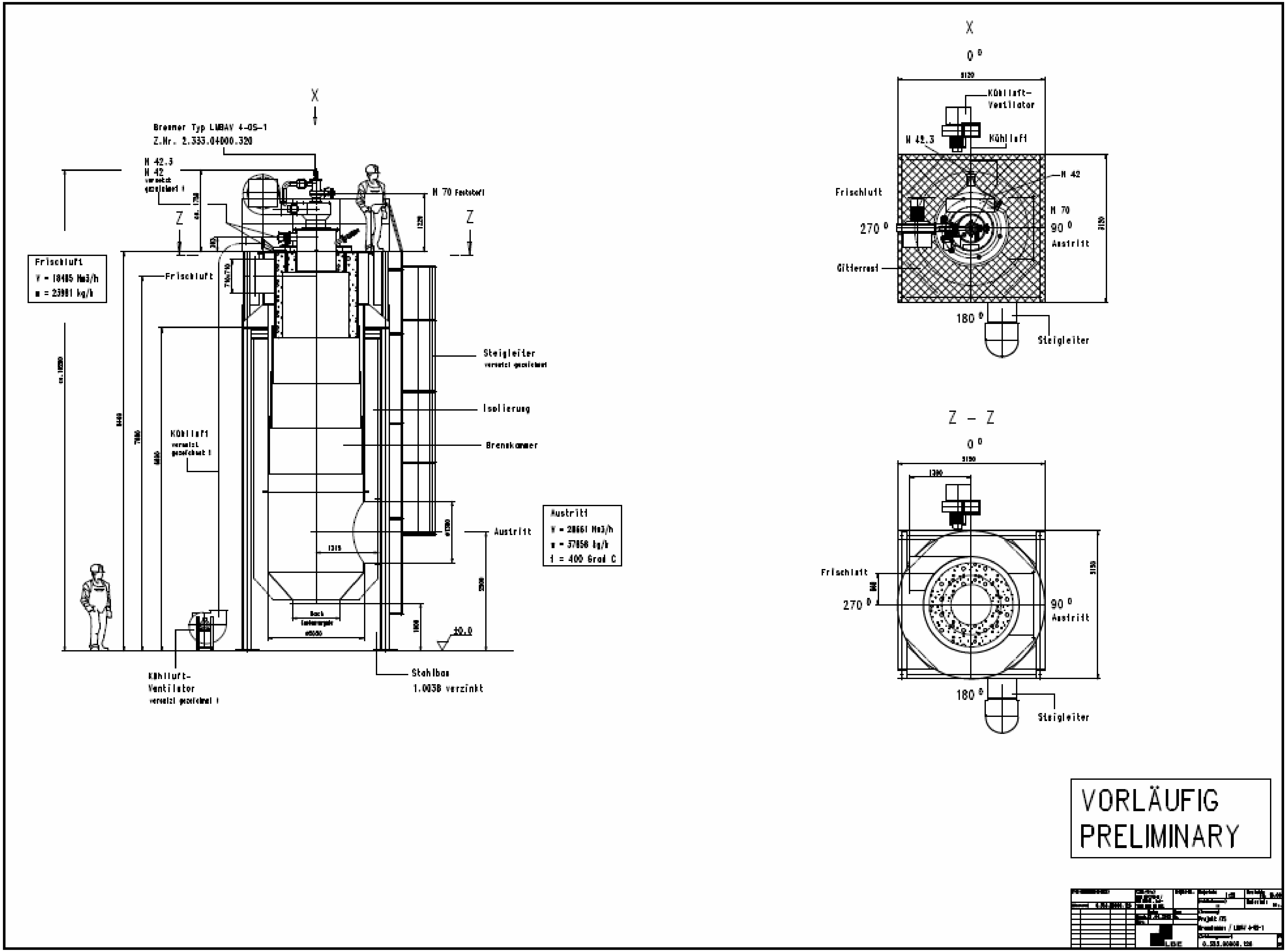
2) A hot gas generator for 4 MW with this burner



Stutzentabelle

N 70	Feststoff
N 60.2	Öl
N 42	Kühlluft
N 41.2	Zentralluft
N 41.1	Hauptluft
N13	Fl.Überwachung
N12	Fl.Überwachung
N11	Zündbrenner
Benennung	Medium

(Verwendungsbereich)
(Ersatz für) 2.333.04000.320
(Zul.Abw.)
Projekt-Nr.
Maßstab: 1:10
Gewicht: ca. 1600
(Artikelnummer) xx
Material: Div.
Datum
Name
Bearb. 28.10.2005 Hu.
Gepr.
(Benennung)
Brenner Typ LHBAV 4-DS-1
Maßblatt
(Zeichnungsnummer)
2.333.04000.320


X
Brenner Typ LUBAV 4-OS-1
Z.Nr. 2.333.04000.320
N 42.3
N 42
versetzt gezeichnet !
N 70 Festbrennstoff
Z
Z
Frischluft
V = 18405 Nm3/h
m = 23981 kg/h
Frischluft
Kühlluft
versetzt gezeichnet !
Steigleiter
versetzt gezeichnet
Isolierung
Brennkammer
Austritt
Austritt
V = 28661 Nm3/h
m = 37058 kg/h
t = 400 Grad C
1315
±0.0
Kühlluft-
Ventilator
versetzt gezeichnet !
Stahlbau
1.0038 verzinkt
X
0°
Kühlluft-
Ventilator
N 42.3
Kühlluft
N 42
Frischluft
N 70
270°
90°
Austritt
Gitterrost
180°
Steigleiter
Z – Z
0°
1300
Frischluft
270°
90°
Austritt
180°
Steigleiter
VORLÄUFIG
PRELIMINARY
Projekt
LBE