

**EVALUATION OF THE COMBUSTION CHARACTERISTICS OF FOUR PERENNIAL ENERGY CROPS
(*ARUNDO DONAX*, *CYNARA CARDUNCULUS*, *MISCANTHUS X GIGANTEUS* AND *PANICUM VIRGATUM*)**

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ABSTRACT: The perennial crops giant reed, switchgrass, miscanthus and cardoon were investigated in laboratory-scale and pilot-scale combustion test runs. Laboratory-scale test runs were conducted in a fixed bed pot reactor monitoring the temperature in the fuel bed and the release of gaseous components while pilot-scale test runs were conducted in a 150 kW_{th} rotating grate fired combustion plant measuring formed emissions of CO, NO_x, SO₂, HCl, and particulates as well as performing deposit probe measurements. The results revealed that the high concentration of ash and slag forming elements such as Si, K and Ca cause severe problems regarding slagging if not specially considered during combustion. Moreover, high concentrations of N are another challenge regarding measures in order to avoid high emissions of NO_x. Moreover, also HCl and SO₂ emissions are considerably higher compared to wood fuels due to the higher concentrations of Cl and S in these fuels.

Keywords: biomass characteristics, biomass conversion, cynara cardunculus, giant reed, switchgrass, miscanthus

1 INTRODUCTION

Due to the limited availability of wood fuels, in southern Europe, high yield energy crops could give an important contribution to biomass based energy production in these countries. The work presented is part of the EU-project BIOENERGY-Chains (No: ENK6-CT2001-00524). The project focus on the investigation of the best possible utilisation chain of selected perennial energy crops, which could be sustainably developed in rural areas of Southern Europe.

Four perennial energy crops, *Arundo donax* (giant reed), *Cynara cardunculus* (cardoon), *Miscanthus x giganteus* (miscanthus) and *Panicum virgatum* (switchgrass) have been selected for this purpose, partly because of their high yield in southern European soils, but also due to their different harvesting time during the year. Consequently, by a combined utilisation of these four energy crops, they can provide a year-around availability of raw material with low demand for storage (see also [1]).

2 OBJECTIVES

Due to the limited amount of experience with these crops as a fuel, the scope of the work presented in this paper is to characterise these energy crops by means of chemical analysis and test runs in a laboratory-scale pot reactor and in a pilot-scale combustion unit (nominal boiler capacity of 150 kW_{th}). Special focus has been set on the evaluation of the formation of emissions such as NO_x, HCl, SO₂ and particles (aerosols) as these parameters have significant influence on the design of a biomass combustion plant and its operation. Furthermore, possible ash related operational problems such as slagging, deposit formation and corrosion have been evaluated as well.

3 FUEL CHARACTERISATION

Samples of pelletised switchgrass (SG), pelletised cardoon (CA) and chopped giant reed (GR) were investigated in a laboratory-scale pot reactor (50-400g). Parallel to these tests, test runs in a pilot-scale

combustion unit (nominal boiler capacity 150 kW_{th}) were carried out with larger amounts (2-4 tons) of pelletised switch grass and chopped giant reed and chopped miscanthus (MI). Pictures of the samples investigated are shown in Figure 1. The fuels investigated were provided from test fields by the partners of the BIOENERGY-Chains project. Giant reed and miscanthus were provided by CRES (Greece) while pelletised switch grass was sent from the University of Bologna (Italy) and pelletised cardoon from the Universidad Politecnica de Madrid (Spain).

As reference to the perennial fuels, Austrian wood pellets (WP) were investigated using the same experimental set up in lab-scale and in pilot-scale combustion test runs. The pilot-scale test runs with wood pellets was performed prior to the test runs with the perennial crops. The combustion technology used was the same, only the nominal boiler capacity was slightly higher (220 instead of 150 kW_{th}) identical and thus the results are considered to be comparable from the results obtained with the perennial fuels.



Figure 1: Fuels investigated: A) pelletised switchgrass (SG), B) pelletised cardoon (CA), C) chopped giant reed (GR), D) chopped miscanthus (MI)

The main elemental compositions, the gross calorific values (GCV) and the bulk density of the fuels investigated including the reference fuel wood pellets (spruce) are revealed in Table I.

Compared to wood, perennial crops typically contain significantly higher concentrations of ash. This is partly due to their fast growing metabolism (accumulation of nutrients) and different organic structure (SiO₂-phytoliths) but can also be significantly influenced by the harvesting period and by the mechanical harvesting technique used. These effects, as well as a comprehensive literature review on the typical composition of these perennial crops are discussed in more detail elsewhere (see [2]).

In the fuel samples investigated (Table I) the highest concentration of ash is found in pelletised CA followed by pelletised SG. Typically, the dominating ash forming elements in the perennial crops are Si followed by K, Ca, Cl and S. The pelletised CA also contains a very high concentration of Na which coincides with its very high concentration of Cl implying high presence of NaCl. High concentrations of Cl and S in combination with high concentrations of K and Na imply that high aerosol emissions as well as considerable deposit formation on boiler tubes can be expected from these volatile elements. During combustion these elements vaporise and condense in the flue gas (forming fine particulates) as well as on heat exchanger surfaces with decreasing flue gas temperatures [3]. Moreover, high concentrations of K and Si can result in the formation of ashes with low melting temperatures and thereby can cause slagging on the grate as well as in the combustion chamber.

Table I: Analyses results of fuel samples investigated
Explanations: SG...switchgrass, GR...giant reed, MI...miscanthus, CA...cardoon, WP...wood pellets, d.b...dry basis, a.f...ash free, GCV...gross calorific value, Bulk dens...bulk density

	SG	GR	MI*	CA**	WP
[wt% d.b.]					
Ash	8.3	6.1	2.3	17.4	0.50
N	0.67	0.71	0.16	1.1	0.08
[mg/kg (d.b.)]					
Si	14,991	13,920	7,305	21,142	< 400
Ca	6,555	3,253	1,776	19,025	938
K	12,756	6,497	1,446	21,546	484
Na	924	331	58	10,330	30
Mg	2,223	1,627	644	3,936	152
Al	763	919	82	4,445	n.a.
S	735	2,160	390	1,566	73
Cl	1,511	2,245	880	17,780	53
[MJ/kg (d.b., a.f.)]					
GCV	17.8	19.8	19.6	20.3	20.3
[kg d.b./m ³]					
Bulk dens.	585	116	117	561	644

The ratio of Cl to S is an indicator on the corrosion potential of fuels by so called "active oxidation", which is explained by local release of corrosive Cl-gas on boiler tubes by sulphation of alkali or heavy metal chloride in deposits. Typically a Cl/S ratio above 1 indicates an increased corrosion potential, which is given for all the

perennials. Especially CA the Cl/S ratios is very high and thereby the potential of corrosion as well.

Compared to wood, the perennial crops also contain higher concentrations of N, which imply higher NO_x emissions. Low GCV and a low bulk density demand larger combustion chambers and fuel feeding systems per unit produced energy and thereby increase the costs of the combustion plant. Following, pelletisation, which increases the bulk density about 5 times, seems to be an interesting approach (see Table I).

4 LABORATORY-SCALE FIXED BED POT REACTOR TEST RUNS

In order to further define and investigate the characteristics and potential problems during combustion of these new fuels, test runs in a lab-scale fixed bed pot reactor were performed. The pot reactor is specially constructed for investigating the release and combustion behavior of biomass fuels in a fixed bed (see also [4]).

The reactor consists of an electrically heated furnace (max. temperature 1,100°C) with a retort and a sample container made of fiber reinforced SiC. The sample container is placed on a weight balance and air is added through a grate on the bottom of the sample container. Before each test run the sample container (0.6 dm³) is completely filled with the fuel sample, and then inserted into the pre-heated oven (750°C) from below (see Figure 2) and sealed by a liquid seal of high temperature stable oil. After an initial drying phase the fuel ignites by the radiation of the furnace and the ignition front proceeds downwards in the fuel sample.

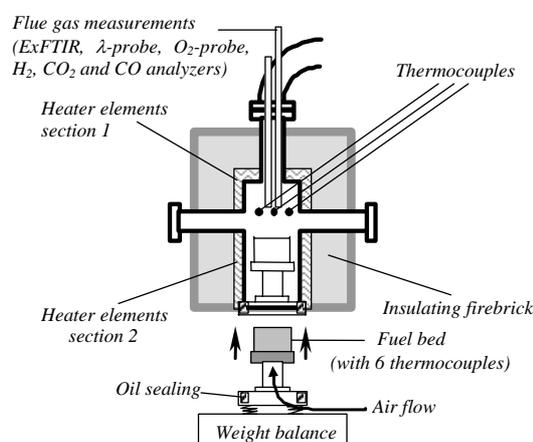


Figure 2: Fixed bed pot reactor

3.1 Measurements performed during the laboratory-scale test runs

The weight loss of the sample during the test runs is measured continuously by a weight balance and the composition of the released flue gas is measured by means of continuous extractive sampling over the fuel bed. The extracted gas is filtered through a heated filter and then diluted (15 times) by nitrogen before it is analysed by means of extractive Fourier transformed infrared analysis (ExFTIR). The ExFTIR (ANSYCO) is used to measure the main flue gas components such as CO, CO₂, CH₄ and H₂O (see Figure 3a) as well as NH₃, HCN, NO and NO₂ (see Figure 3b). Online measurements of HCl and SO₂ under air reach conditions ($\lambda > 1$) have been performed by ExFTIR as well.

However, evaluations of the results showed that during air lean combustion conditions ($\lambda < 1$), which prevail after ignition during the first half of the pot reactor tests, other S and Cl compounds than HCl and SO₂ are formed which could not be detected by the ExFTIR library used for the evaluations so far.

Downstream of the ExFTIR, the concentration of H₂ is measured by heat conductivity (NGA 2000 MLT1) and CO₂ and CO are measured by means of conventional IR-photometry (NGA 2000) as a check of the ExFTIR measurements. O₂ is measured by lambda probes before and after the dilution as well as by a conventional O₂-probe downstream of the ExFTIR.

Six thermocouples are placed in different positions inside the fuel bed which makes it possible to investigate the temperature profiles formed. Moreover, due to the different locations of the thermocouples, the burning front in the bed is revealed as the time delay between the temperature increase of each thermocouple (see Figure 3c). The temperature of the flue gas is measured by another three thermocouples in the free board over the bed.

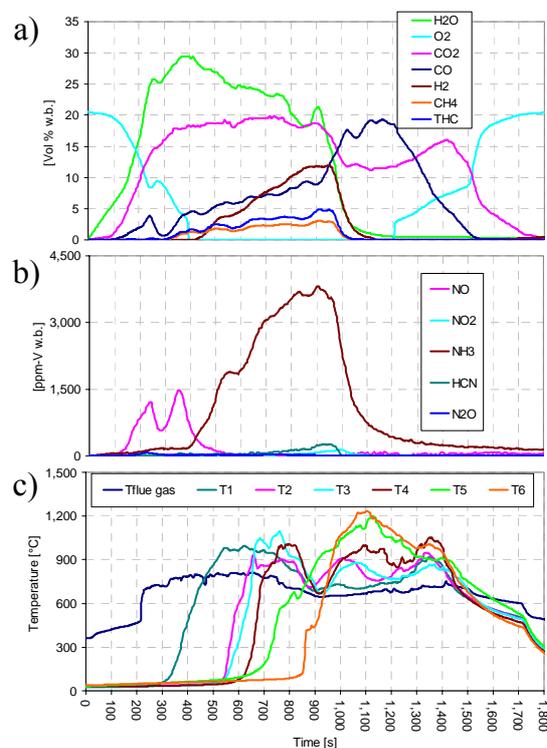


Figure 3: Result of a lab-scale reactor test run with SG;
a) release of main flue gas components,
b) release of N species,
c) temperature profiles in the fuel bed and flue gas
Explanations: SG pellets, furnace pre heated to 750°C,
30 Ndm³/min of air flow...

5 PILOT-SCALE COMBUSTION PLANT TEST RUNS

Test runs were conducted at the company KWB - KRAFT UND WÄRME AUS BIOMASSE GMBH in their newly developed 150 kW_{th} TDS-powerfire combustion plant [6], which has been specially designed for the combustion of solid biomass fuels with high moisture and high ash contents. The plant is

automatically controlled and equipped with a rotating grate furnace (A in Figure 4), a cyclone burner as secondary combustion chamber (B in Figure 4), improving the complete burn out of the flue gases, as well as flue gas recirculation into the primary combustion chamber for temperature control. The boiler tubes are equipped with turbulators which improve the efficiency of the boiler but also work as cleaning equipment for the boiler tubes (C in Figure 4).



Figure 4: 150 kW_{th} pilot-scale combustion plant used for the test runs

Explanations: A...rotating grate, B...cyclone burner, C...boiler with automatic cleaning, D...location for deposit probe measurements

4.1 Measurements performed during the pilot scale test runs

Continuous measurements of the flue gas composition downstream the boiler and the flue gas fan, were performed by multi-component ExFTIR (ANSYCO) measuring CO₂, CO, H₂O, HCl, SO₂ and NO_x (NO, NO₂). The data obtained by the ExFTIR were checked by parallel measurements of CO, CO₂ and NO_x (NO and NO₂) by conventional photometric and chemiluminescence analytic equipment as well as by extractive sampling in impinger bottles for subsequent wet chemical analyses (for Cl and S).

Oxygen was measured by means of an external O₂-probe in the same sampling line of the ExFTIR and by the λ -probe included in the controlling system of the combustion plant.

Moreover, discontinues measurements including total dust measurements (VDI 2066), as well as particle size distribution measurements, by a Berner type low pressure impactor (BLPI) were carried out during all test runs.

Furthermore, samples were collected from fuel and all ash streams (bottom ash, slag, cyclone fly ash and heat exchanger ash) for subsequent chemical analyses.

Operational data from the system such as temperatures, concentration of oxygen in the flue gas and load were recorded during each test run.

Furthermore, deposit sampling by means of an air cooled probe was performed upstream the boiler section (D in Figure 4). Deposits were collected at different surface temperatures of the probe (180°C and 350°C) as well as using different sampling durations (0.5-14 hours).

6 RESULTS

Average results regarding relevant operational data from the test runs in the lab-scale and the pilot-scale plant are displayed in Table II and Table III.

Table II: Typical operational data from the lab-scale test runs

Explanations: bed T...temp in the fuel bed, f.g.T...flue gas temperature over the fuel bed, w.b...wet basis, n.a.f...non ash free

	Unit	SG	GR	CA	WP
Sample	[g]	377	72	374	426
Max bed T.	[°C]	1,243	892	1,230	1,231
Max f.g. T.	[°C]	895	790	846	765
Moisture	[wt% w.b.]	9	12	7	8
Ener. dens.	[MJ/m ³]				
NCV	[n.a.f. w.b.]	9,620	2,111	10,577	12,090

The most significant difference between the fuels investigated is the bulk density (Table I) and thereby also the energy density between chopped and pelletised fuels. Due to the lower energy density of the chopped fuels (GR and MI), lower amounts and lower fuel bed temperatures were obtained during the lab-scale test runs (GR in Table II) and lower loads were obtained during the pilot-scale test runs (GR and MI in Table III) in comparison to the pelletised fuels.

Table III: Average data from pilot-scale combustion test runs

Explanations: Prim T...primary combustion temp, Sec. T...secondary temperature just before the boiler; w.b...wet basis, n.a.f...non ash free

	Unit	SG	GR	MI	WP
Average load	[kW]	93	71	55	223
Total hours of test run	[h]	19	45	19	7
Mean Prim. T.	[°C]	850	990	735	1,043
Max Prim. T..	[°C]	1,071	1,243	1,121	1,130
Mean Sec. T.	[°C]	660	630	550	1,141
CO ₂	[Vol% w. b.]	10	8	8	13
H ₂ O	[Vol% w. b.]	11	11	9	12
Moisture	[wt% w.b.]	9	22	14	8
Ener. dens.	[MJ/m ³]				
NCV	[n.a.f. w.b.]	9,620	2,068	1,962	12,090

The combustion of WP was performed in the TDS plant prior to re-construction and thus a higher load than 150 kW was realised during these experiments. The main significant effect was a significantly higher flue gas temperature in the secondary combustion chamber. The GR used in lab-scale test runs was drier than the fuel used in the pilot plant due to natural drying which took place during storage in the lab.

5.1 Emissions

The average emissions measured during the combustion test runs in the pilot-scale plant are listed and compared to limiting values for small-scale combustion plants firing chemically non treated wood waste and natural wood in Austria [7] in Table IV.

As expected, the emissions of HCl, SO₂ and NO_x comply with the concentrations of Cl, S and N in the fuels (see Table I and Table IV). An exception represent the emissions of HCl from SG which are lower than from MI although SG contains higher concentrations of Cl. But SG contains a much higher concentration of K, therefore the main part of Cl is bound as solid KCl. This can also be seen in the higher dust and aerosol emissions from the test runs with SG.

Table IV: Average emissions measured during test runs in the pilot-scale combustion plant

Explanations: <1µm...particle emissions smaller than 1µm (aerosols), limits...Austrian limiting values for chemically non treated wood waste* or natural wood** fired combustion plants (100-350 kW) [7]

	SG	GR	MI	WP	limit
	[mg/Nm ³ (13% O ₂ , d.b.)]				
Total dust	58	102	27	21	150
< 1µm	50	67	16	16	
NO _x	368	363	187	106	*350 **250
HCl	18	67	59	3	
SO ₂	91	278	53	3	
CO	145	443	55	1	250

Due to the low energy density of the chopped fuels (GR and MI), a much higher fuel bed had to be kept in the pilot-scale test runs in order to achieve a reasonably high load with these fuels. Due to this high fuel bed and also to the very light fuel particles of the chopped fuel a high entrainment of fuel particles with the flue gas occurred. This entrainment of fuel particle decreased the burn out of the flue gas (increased the emissions of CO) and also increased the dust emissions. The effect of entrained fuel and ash particles is also seen by comparing the ratio of emitted particles smaller than <1µm with the total emissions of dust in Table IV. While the dust emissions from the pelletised fuels (SG, WP) almost entirely consist of particles <1µm, the dust from the combustion of chopped fuels contains a larger portion of particles >1 µm as well.

HCl and SO₂ emissions from the combustion of the perennial crops are significantly higher than from the test runs with WP. However, currently no limiting values for these compounds are given in Table IV because values have been derived for wood fuels. In case of an increased thermal usage of perennial or annual crops e.g. wheat straw also limiting values for SO₂ and HCl are to be expected for small-scale applications in the future.

The high average CO emissions of SG were due to severe slagging on the grate which disturbed the flow of primary air through the fuel bed.

Compared to the limiting values for wood combustion in Austria, the test runs with SG exceeded the NO_x and GR the NO_x and CO emission limits.

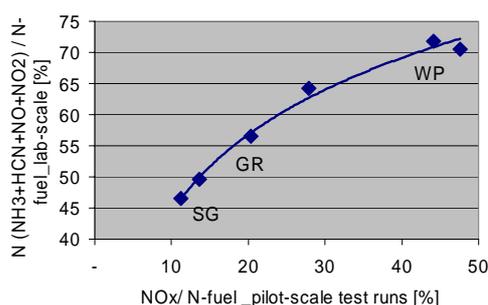


Figure 5: Comparison of N-conversion ratios in laboratory-scale pot reactor test runs to N-conversion (NO_x formation) ratios in the pilot-scale test runs

Moreover, by plotting the conversion ratios of $(\text{NH}_3 + \text{HCN} + \text{NO}_2 + \text{NO})/\text{N-fuel}$ in the lab-scale test runs against the conversion ratios of NO_x formation in the pilot-scale test runs ($\text{NO}_x/\text{fuel-N}$), a correlation resulted (see Figure 5). This correlation is encouraging and implies that the NO_x emissions from the pilot-scale test runs could be predicted by test runs in the lab-scale reactor. However, the results are based upon a rather limited amount of data so far and thus more test runs are necessary to secure these results and also comparisons to other combustion plants have to be made in order to secure the prediction efficiency of the lab-scale results.

5.1 Slagging

Slagging was observed within the first 12 hours of operation during all test runs with the perennial crops investigated in the pilot-scale combustion plant. In the lab-scale test runs molten ash was only observed in the test runs with pelletised perennial crops (SG and CA) in which the max temperature in the bed exceeded $1,200^\circ\text{C}$ (see Table II). No slagging was observed during test runs with wood pellets and the test runs with chopped GR, due to the high melting temperature of wood ash and due to the low bed temperature achieved for chopped GR.

Chosen slag samples from the pilot-scale test-runs and molten ash from the lab-scale test runs were analysed by means of scanning electron microscopy (SEM) and energy dispersive X-ray analysis (EDX). The elemental composition of these slag samples is shown in Table V.

Table V: Average composition of slag samples from pilot-scale and molten ash from lab-scale test runs
Explanations: *...sample from lab-scale test runs

	SG	SG*	GR	MI	CA*
	Weight %				
Si	25	24	33	34	29
K	14	21	9	7	17
Ca	7	14	6	9	9
Mg	3	5	2	2	-
P	1	2	1	-	-
Al	4	3	1	-	7
Na	1	1	-	-	5
Fe	2	4	-	-	7
O	42	25	47	47	26

The results reveal that the composition of the slag and molten ash samples is quite similar for all the fuels, except for cardoon (CA). By exclusion of O, which is calculated assuming complete oxidation of all other

elements, the main component of the melt is Si followed by K and Ca. Thus, the composition of the slag and molten ash samples were recalculated as oxides (only considering Si, K, and Ca) and plotted in the ternary phase system $\text{SiO}_2\text{-K}_2\text{O-CaO}$ (Figure 6). In this diagram the area where melting occurs below $1,200^\circ\text{C}$ is indicated. Furthermore, for comparison also the concentrations of Si, K and Ca in the fuel (see Table I) were recalculated as oxides and plotted into the diagram (fuel ash in Figure 6).

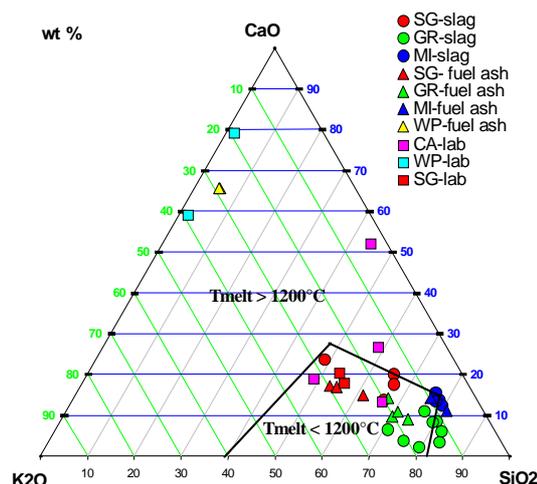


Figure 6: Composition of slag and fuel ash plotted in the ternary phase diagram $\text{SiO}_2\text{-K}_2\text{O-CaO}$

The results reveal that all the ashes and slag samples investigated from the perennial crops are found inside the area where the melting temperature is below $1,200^\circ\text{C}$. An exception represent the ashes from cardoon from WP. The complex composition of CA which also includes greater amounts of Na and Al suggest that a more complex phase diagram than the $\text{SiO}_2\text{-K}_2\text{O-CaO}$ is necessary to describe the melting behaviour of CA ash.

Furthermore, the results also show that the ratio between the main slag forming elements K, Si and Ca are similar in the fuel ash and in the slags from the respective fuels investigated. This result suggests that a good estimation of the composition of slag and molten ash from these fuels should be possible from fuel analyses. More analyses should be performed in order to confirm this observation, supplemented by appropriate ash melting tests.

5.3 Deposit formation

Deposit samples were collected by means of an air-cooled probe inserted upstream of the boiler during the pilot-scale test runs. The mass increase of the rings versus the sampling time are shown in Figure 7 for the fuels investigated. Moreover, the surfaces of the rings (luv and lee side) were investigated by means of SEM/EDX.

The highest deposit growth rates were measured for SG and GR. These fuels also revealed the highest dusts emissions (see Table IV) and contain the highest amounts of K and Cl (see Table I).

The results from SEM/EDX analyses (SG after 4 h sampling, GR and MI after 2h sampling) revealed almost pure KCl as the major constituent on all rings, with small amounts of S and Na (2-4 wt%). No significant

differences between luv and lee side of the rings were observed. Following, it can be concluded that the concentrations of K and Cl in the fuels are the most important factors for the initial growth of deposits on low temperature boiler tubes during the combustion of perennial crops. Analyses of the two 14 h samples are still to be conducted and will give more information on eventual changes in the deposit (e.g. sulphation) with time.

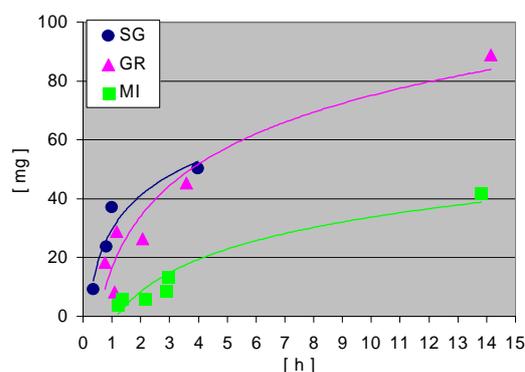


Figure 7: Deposit growth on an air-cooled probe (180°C) upstream the boiler section in the pilot-scale test runs for the fuels investigated

The collected deposits were only loosely bound to the surface and are thus not expected to cause severe problems if automatic boiler cleaning systems are installed. However, due to the high content of Cl in these deposits and the high concentrations of SO₂ in the flue gas, the potential for corrosion by “active oxidation” is high, especially increasing temperatures of the boiler tube surfaces (e.g. in steam boilers). Moreover, by stop and go operation of the plant care has to be taken that no condensation of moisture occurs in the boiler as this could significantly increase corrosion by dissolving the hygroscopic KCl on the boiler tube surface.

7 DISCUSSION AND CONCLUSIONS

Test runs with the perennial crops SG, CA, GR and MI revealed that combustion of these crops is challenging and can only be performed if special care is taken regarding the combustion and process control technology used. The results revealed that for all four crops either molten ash in lab-scale test runs or slag in the pilot-scale combustion plant were formed, which significantly disturbs the combustion process and reduces the achievable boiler load and availability. Moreover, significantly higher emissions of particulates as well as of gaseous emissions of HCl, SO₂ and NO_x were observed from these test runs compared to test runs with wood pellets. The problems described are related to the composition of these fuels comprising high ash contents with high concentrations of especially Si, K and Ca (forming low temperature melting ash) as well as high concentrations of Cl, S and N resulting in increased gaseous emissions.

Operational measures to decrease the tendency of slag formation would be to decrease the temperature of combustion by using cooled grates and for furnace walls in the combustion chamber.

Another approach would be to upgrade the fuels by either separating problematic elements (eg. through leaching) or trying to neutralise their effects by additives (e.g. addition of lime to increase the melting point of the slag).

A third possibility would be to blend the perennial crops with wood fuels. By blending with wood, also the HCl, SO₂, NO_x and particles emissions are expected to decrease due to the dilution effects achieved. First tests with fuel blends confirmed these expectations for small scale combustion. This approach is probably the best way to introduce these new crops into the market. But comprehensive test runs with fuel blends are necessary in order to optimise the blending ratios

Moreover, by comparing the results from the lab-scale test runs with results from the pilot-scale test runs, similar effects were observed for at least pelletised fuels. This implies that lab-scale reactor test runs could be a useful and cheap method for first screening tests for new and unknown biomass fuels regarding their slagging properties and emission potentials.

8 ACKNOWLEDGEMENT

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