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FUEL FLEXIBLE AND LOW-EMISSION BIOMASS COMBUSTION BY COMBINATION OF FUEL ADDITIVATION AND COMBUSTION RELATED PRIMARY MEASURES

Christoph Mandl[1], tel: +43 316 48130022; fax: +43 316 481300 4; email: mandl@bios-bioenergy.at
Ingwald Obernberger[1], tel: +43 316 48130012; email: obernberger@bios-bioenergy.at
Holger Knautz[2], tel: +43 2672 89076; email: h.knautz@polytechnik.at
[1] BIOS BIOENERGIESYSTEME GmbH, Hedwig-Katschinka-Straße 4, A-8020 Graz, Austria
[2] POLYTECHNIK Luft- u. Feuerungstechnik GmbH, Hainfelderstrasse. 69, A-2564 Weissenbach, Austria

ABSTRACT: The demand for wood fuels for biomass heating and CHP plants is steadily increasing, thus the prices also rise accordingly, which results for more and more plant owners in economic problems. The utilisation of non-wood biomass fuels, e.g. Miscanthus, grass and agriculture residues such as straw, corn cobs or sunflower husks would be a possible alternative, but due to ash-related problems (slagging, deposit formation, corrosion and enhanced particulate matter emissions) these fuels cannot be used in conventional biomass heating systems designed for wood fuels so far. Within a nationally funded Austrian research project a new, fuel flexible and low-emission combustion technology in the power range from 300 to 1,000 kW_{th} for ash-rich fuels with low ash melting temperatures (non-wood biomass fuels) has been developed. The application of optimised fuel additivation in combination with combustion related primary measures (appropriate air staging and bed cooling) form the basis to overcome ash-related problems. Test run results show that this technological approach provides significantly enhanced fuel flexibility at reduced emissions, compared to present state-of-the-art systems for small- to medium-scale applications without cost intensive secondary measures. With the technological additional fuel assortments (non-wood biomass fuels) may be utilised in an economically competitive way, which enlarges the available biomass fuel potential and increases the flexibility for the user.

Keywords: agricultural residues, additives, staged combustion, primary measures, emissions

1 INTRODUCTION AND OBJECTIVES

The demand for wood fuels for biomass heating and CHP plants is steadily increasing, thus the prices also rise accordingly, which results for more and more plant owners in economic problems.

The utilisation of non-wood biomass fuels, e.g. Miscanthus, grass and agriculture residues such as straw, corn cobs or sunflower husks would be a possible alternative, but due to ash-related problems (slagging, deposit formation, corrosion and enhanced particulate matter emissions) these fuels cannot be used in conventional biomass heating systems designed for wood fuels so far. Currently available biomass heating systems for the utilisation of non-wood biomass fuels need a high system complexity and cost intensive secondary measures have to be applied to keep strict emission limits. Even if there has been a steep further development of biomass combustion systems towards low emissions and higher fuel flexibility during the last decades, still some disadvantages compared with emissions of fossil fuel fired systems exist.

Within a nationally funded Austrian research project a new, fuel flexible and low-emission combustion technology in the power range from 300 to 1,000 kW_{th} for ash-rich fuels with low ash melting temperatures (non-wood biomass fuels) has been developed. The application of optimised fuel additivation in combination with combustion related primary measures (bed cooling) form the basis to overcome ash-related problems and thereby widen the feedstock basis for biomass heating and also CHP application. Furthermore, a second relevant aim was to achieve a fuel flexible and economically attractive solution without the need of excessive additional flue gas cleaning (i.e. bag filter or electrostatic precipitator).

The technological development has strongly been supported by detailed investigations of the ash chemistry in the fuel bed as well as by CFD (Computational Fluid Dynamics) simulations in order to design and optimise the burner. Furthermore, a testing plant was constructed and comprehensive test runs with accompanying measurements and analyses have been performed to evaluate the performance of the new technology and to validate the additivation strategy. Based on the data and experiences gained from the test runs a technological assessment of the testing plant has been performed.

2 TECHNOLOGICAL APPROACH

2.1 Basic research regarding the ash-melting behaviour of non-wood biomass fuels and fuel additivation

Ash related problems, namely slagging, deposit formation as well as fine particulate emissions are the main reasons why agricultural fuels presently cannot be utilised in plants designed for wood combustion. Therefore, one aim of the work presented in this paper was to develop an additivation strategy for agricultural biomass fuels, which shall be applied to improve their combustion related properties in order to overcome ash related problems as successful research [1, 2] has already shown that slagging, aerosol and deposit formation could significantly be reduced by fuel additivation.

In a first step relevant agricultural fuel have been evaluated based on fuel indexes. Fuel indexes are defined in order to provide first qualitative indications regarding relevant combustion related properties of biomass fuels such as the potential for gaseous NO_x, SO_x and HCl emissions, the potential for the formation of fine particulate emissions as well as the ash melting behavior [3]. In comparison with conventional wood chips agricultural fuels like wheat straw or miscanthus distinguish themselves by elevated N, S, Cl and ash contents as shown in Table I. The ash compositions, which can be estimated from the fuel composition, indicate for miscanthus and wheat straw K and Si dominated systems while wood chip ashes are rich in Ca and K.

Table I: Chemical compositions as well as relevant fuel indexes
Explanations: w.b. … wet basis; d.b. … dry basis; see [3] for description of fuel indexes

		Wheat straw	Miscanthus	Wood chips
moisture	wt% w.b.	11.0	8.5	18.6
ash content	wt% d.b.	6.5	2.56	1.47
C	wt% d.b.	45.0	48.0	49.5
H	wt% d.b.	5.8	6.0	5.9
N	wt% d.b.	0.49	0.28	0.14
S	mg/kg d.b.	926	560	173
Cl	mg/kg d.b.	1,730	1,020	93
Si	mg/kg d.b.	19,000	5,340	536
Ca	mg/kg d.b.	2,920	1,320	3,160
Mg	mg/kg d.b.	978	519	505
K	mg/kg d.b.	7,990	5,340	1,430
Na	mg/kg d.b.	84	72	14
P	mg/kg d.b.	510	494	97
Al	mg/kg d.b.	388	133	81
Fe	mg/kg d.b.	202	193	49
Mn	mg/kg d.b.	29	46	28
Zn	mg/kg d.b.	10	16	6
K+Na+Zn	mg/kg d.b.	8,084	5,428	1,450
(Si+P+K)/(Ca+Mg+Al)	mole/mole	7.04	5.8	0.57
Cl/Si	mole/mole	0.07	0.15	0.14
2S/Cl	mole/mole	1.18	1.21	4.14

For an increasing value of the ash melting index ([Si+P+K]/[Ca+Mg+Al]) decreasing ash melting temperatures are expected. Consequently, the high values for miscanthus and wheat straw indicate very low melting temperatures. This can also be derived from Fig. 1, where the ash melting index and shrinkage starting temperatures determined with the standard ash melting test according to CEN/TS 15370-1 of the fuels investigated are compared with database values for herbaceous fuels and chemically untreated wood fuels.

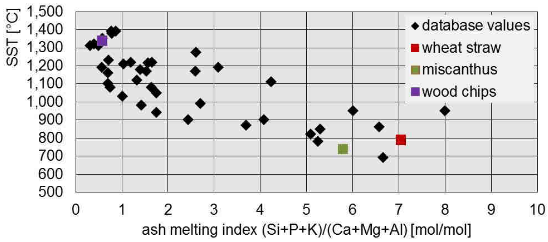

Figure 1: Qualitative evaluation of miscanthus, wheat straw and wood chips based on the ash melting index
Explanations: SST … shrinkage starting temperature according to CEN/TS 15370-1; database values taken from the biomass fuel database of BIOS BIOENERGIESYSTEME GmbH

The interpretation of the K-release index relies on the fact that high Cl contents support the release of K to the gas phase while high Si contents favor the embedding of K in K-silicates, thus with increasing index value also the release increases. In Fig. 2 the K release rates of herbaceous fuels and chemically untreated wood fuels are shown. For miscanthus and wood chips K release rates in the range of 15 to 35% and 5 to 15% for wheat straw have to be expected if state-of-the-art fixed-bed combustion technology is applied (Fig. 2). The K release rate seems to be low for wheat straw but due to the high K content of wheat straw high fine particulate emissions can be expected [1].

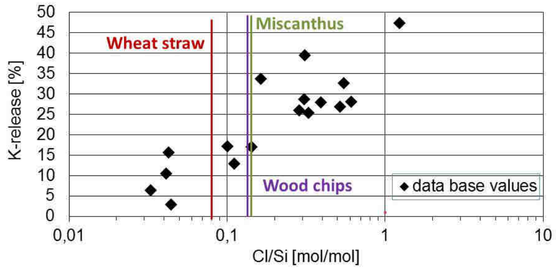

Figure 2: K-release rates of herbaceous fuels and chemically untreated wood fuels in dependence of the molar Cl/Si ratio in state-of-the-art grate-fired boilers
Explanations: database values taken from the biomass fuel database of BIOS BIOENERGIESYSTEME GmbH [3]

According to the evaluation of fuel indexes, the following priorities regarding the definition of appropriate additives have been defined:

- Miscanthus: main objectives: to increase the ash melting temperatures and to further reduce the K-release
- Wheat straw: main objective: to increase the ash melting temperatures and to reduce the K-release

In the following different options regarding additives and their impact on ash melting behaviour and K-release have been studied. It is expected that alumo-silicates such as kaolin increase the ash melting temperatures and foster the embedding of K in these solid phases.

To investigate the effects of different additives in detail, thermodynamic equilibrium calculations (TEC) using FACTSAGE have been performed. TEC can be applied for the prediction of multi-phase equilibria and the identification and quantification of the liquid and solid phases, for a multi-component thermodynamic system in a pre-determined gas atmosphere as well as for the theoretical prediction of the characteristic ash melting temperatures. As an example for these calculations Fig. 3 shows results for wheat straw as well as mixtures of wheat straw with kaolin (4 wt% additive in the mixture).

From the top diagram in Fig. 3, it can be revealed that at temperatures above 750°C an abrupt transformation of solid K-Si-Phases into slags takes place. With further increasing temperatures, these phases become more and more dominant. It has been found that the temperature at which TEC show that 30% of the ashes are molten (T_{30}), usually corresponds with the shrinkage starting temperature (SST) according to the CEN/TS 15370-1 ash melting test [7]. This is also confirmed by the data presented in Fig. 3, where for wheat straw a T_{30} of 786°C

(SST: 790°C) could be identified.

For kaolin addition an increase of the ash melting temperatures to 1,026°C (T_{30}) can be observed which is due to the formation K-alumo-silicates that melt at higher temperatures than K-silicates. The increase in melting temperatures is not that pronounced, but due to the embedding of K in the alumo-silicates, the K-release is significantly reduced.

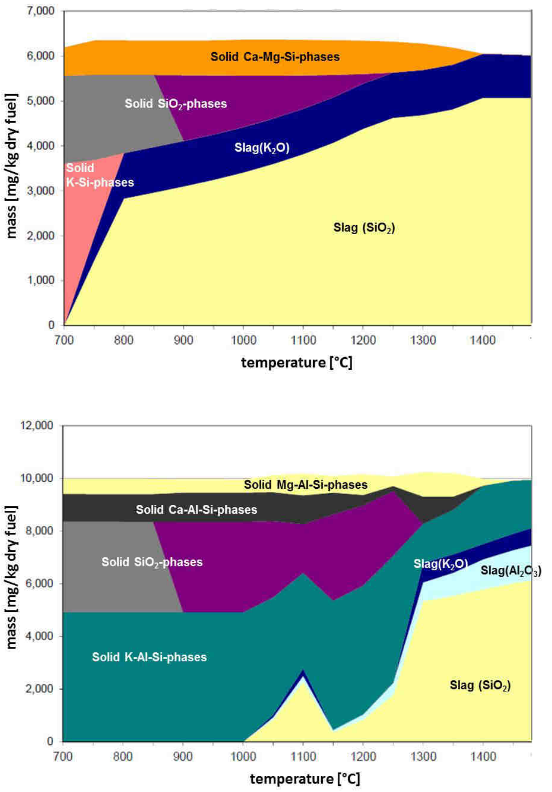

Figure 3: The effects of kaolin addition to wheat straw on ash and slag formation – results from TEC
Explanations: top: wheat straw; bottom: mixture of wheat straw with 4% kaolin

Based on the results of the evaluation of fuel indexes as well as the TEC, the following fuel/additive-mixtures have been proposed for the test runs to gain quantitative experimental data, especially on the ash melting behavior as well as on the K-release:

- miscanthus/ kaolin (0-2 wt.% additive related to dry fuel)
- wheat straw / kaolin (4 wt.% additive related to dry fuel)

The fuel/additive-mixtures proposed were applied during test runs at the testing plant developed to validate the effects achievable in real-life combustion environment.

2.2 The basic approach for fuel flexible and low emission combustion

From the beginning the objective of BIOS and Polytechnik was focused on the development of a new, fuel flexible and low-emission combustion technology which operates at low CO, OGC (organic gaseous carbon) and PM emissions, reduced NO_x (nitrogen oxides) emissions and significantly enhanced fuel flexibility. It was also a declared target to achieve this goal only by the application of optimised fuel additivation in combination with combustion related primary measures, i.e. without the need for any filter. After intensive initial fundamental research on emission formation, especially on PM emission formation, it quickly became clear that the ambitious targets could not be achieved with a conventional combustion technology. Therefore, a new concept with regard to state-of-the-art biomass heating systems had to be developed.

Several technological constraints to achieve the desired low emission operation have been defined. Fine PM emissions from biomass combustion consist of inorganic particles (mainly potassium-salts), organic particles and soot. The chemical composition of the fuel, especially the K-content, determines the potential for aerosol emission formation. The fuel index K + Na + Zn + Pb indicates the potential for the formation of fine particulate emissions. Fig. 4 clearly shows a trend of increasing aerosol emissions with increasing values of this index, whereas for example straw is located at the upper end of the data. The trend displayed is mainly influenced by the K concentration in the fuel or, more precisely, the K release from the fuel to the gas phase.

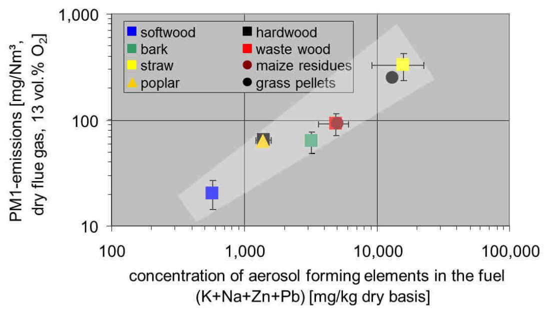

Figure 4: PM_1 emissions versus the concentration of aerosol-forming species (K + Na + Zn + Pb) in the fuel

Therefore, to reduce the emissions of inorganic fine PM, the release of potassium (K) from the fuel to the gas phase must be decreased. This can be achieved by fuel additvation to some extent as shown is section 2.1, but a further decrease of the release of K from the fuel bed has to be achieved. Thus, the temperatures in the fuel bed should be kept on a moderate level as shown in Fig. 5.

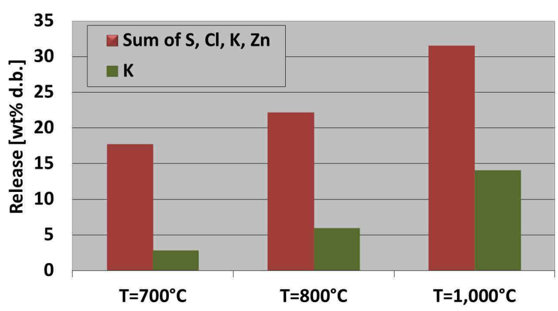

Figure 5: Release of K from the fuel bed as a function of the fuel bed temperatures
Explanations: Release of elements (sum of S, Cl, K, Zn) and of K for different fuel bed temperatures during charcoal combustion; results from test runs with softwood pellets at a lab-scale fixed-bed reactor

This effect cannot be achieved with conventional combustion technologies and therefore, the reduction of the K-release by means of active bed cooling in combination with appropriate air staging was one central issue for the technology development.

Organic PM and soot particles are products of an insufficient burnout and therefore another challenge for the technology to be developed was to gain an almost complete gas phase burnout. During full load operation modern biomass boilers operate at almost complete burnout and therefore, the concentrations of organic carbon and soot in the aerosols are rather low (<10 wt%). During partial load operation the concentration of carboneceous species may increase to values up to 30 wt% which is a result of decreased burnout quality and of the comparably low temperatures in the burnout zone [4].

Finally, also the gas velocities at the fuel bed outlet should remain on a low level to keep the entrainment of unburned fuel, charcoal and ash particles at a minimum and thereby minimise coarse PM emissions. Moreover, the new combustion technology should show a good partial load operation capability throughout full load, partial load and transient operation phases.

A number of feasible concepts were carefully evaluated and finally a concept based on extremely staged combustion coupled with novel bed cooling measures turned out to be the most promising approach. Extremely staged combustion in this case means, that the fuel bed is operated at low air to fuel ratios and the gases released from the fuel are burned in a directly connected downstream multi-stage gas burner (see Fig. 6). The gas burner is applied with multiple air staging for a Low-NO_x-combustion of the gases released from the fuel bed.

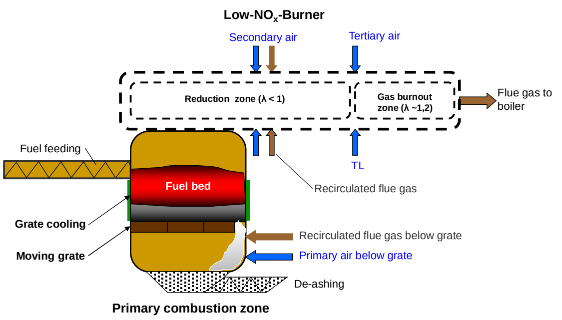

Figure 6: Basic concept of the new fuel flexible and low emission combustion technology

2.3 Technology development

In a next step, basic concepts for the fuel bed section and the gas burner were developed by BIOS.

A special emphasis was put on implementing theoretical considerations and TEC results regarding ash formation and K-behaviour in the dimensioning and design of the fuel bed section. The main aim was to realise a concept that leads to an almost complete embedding of K in the grate ash and thereby minimises inorganic fine PM emissions. With the application of active cooling of the grate section of the fuel bed a high embedding of K in the bottom ashes may be achieved. This is due to the fact that because of the temperature profile in the fuel bed, the hot zone where the release of K takes place is located at the bottom of the fuel bed. The flue gases have then to pass through the fuel bed where they are cooled and most of the K released is condensed (precipitated) again, finally ending up in the ashes. Consequently, due to the lack of gaseous K-compounds in the flue gas above the fuel bed also the potential for inorganic aerosol formation is significantly reduced.

An in-house developed simulation code for fixed-bed biomass conversion to design the fuel bed section with respect to appropriate temperature and gas flow distributions has been applied [5]. The simulation code has been used for agricultural fuels by considering the specific properties of these fuels like ash and moisture contents as well as particle and bulk density. The model has been applied in order to evaluate the influence of active bed cooling by means of:

- recirculated flue gas (addition to primary air)
- grate cooling (by water cooled tubes)

In Fig. 7 simulation results regarding the temperature profiles over the height of the fuel bed are presented for the operation with and without recirculated flue gas below grate (addition to primary air) for pelletized maize combs as fuel under consideration of a fuel moisture content of 10 wt.% (w.b.).

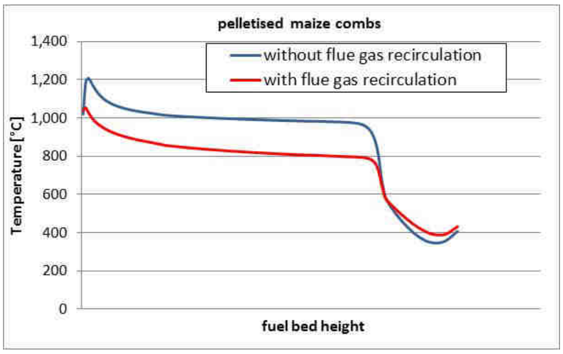

Figure 7: Axial profiles of fuel bed temperatures – bed cooling by addition of recirculated flue gas to primary air

Explanations: air and recirculated flue gas supplied below grate (x=0); ratio recirculated flue gas: 40 wt.% (related to total supplied mass below grate) fuel: pelletised maize combs (fuel moisture content: 10 wt.% w.b.)

Fig. 7 clearly indicates that due to the addition of recirculated flue the bed temperatures in the grate section can be significantly reduced (up to 150 K). The reduced fuel bed temperatures should lead to reduced release rates of Potassium and thereby to lower fine particulate emissions. Furthermore, the ash related problems like ash melting may not occur due the lowered fuel bed temperatures.

Regarding the gas burner design and optimisation, BIOS applied CFD (Computational Fluid Dynamics) simulations. Table II gives an overview over the CFD models considered. In order to carry out the CFD simulations a special code considering the conversion of tars released from the fuel bed has been developed and applied [8]. Moreover, an in-house developed CFD code regarding NO_x formation has been applied in order to optimise the burner geometry and air staging strategies regarding Low-NO_x operation [7].

Here the aim was to find a burner configuration (geometry, number and orientation of combustion air injection points) which enables an almost complete burnout and therefore low CO, OGC and organic PM emissions at low excess air (see Figure 8).

Table II: Overview over CFD models applied

	model
Fixed bed combustion	Empirical in-house model [6]
Turbulence	Realizable k-ε- Model
Gas phase combustion	Eddy Dissipation Mode global methane 3-step mechanism (CH_4, CO, CO_2, H_2, H_2O und O_2)
Radiation	Discrete Ordinates Model
Shell-conduction model	3D - heat conduction in the metal sheet surrounding the combustion zone
Tar conversion model	Extension of the gas-phase-model with nitrogen-free and nitrogen containing tars, each with oxidation and thermal decomposition reactions [8]

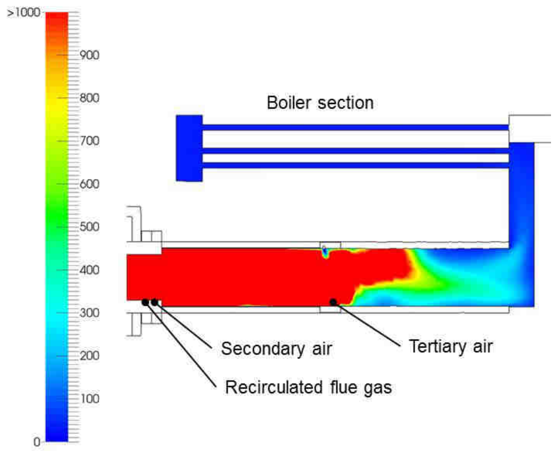

Figure 8: Design of the gas burner – optimisation of flue gas burnout
Explanations: Iso-surfaces of CO concentrations [ppmV] in the vertical cross-section of the combustion chamber; fuel: wood chips (fuel moisture content 34 wt.% w.b.); boiler load: 400 kW

To achieve an optimised mixing of the combustion air with the gases released from the fuel bed as well as appropriate temperature and residence time profiles are thereby the main challenges (see Figure 9). Additional CFD simulations have been performed in order to optimise the burner geometry and air staging strategies regarding Low-NO_x operation [9].

Based on the concepts developed Polytechnik designed and manufactured a testing plant with a thermal capacity of 400 kW which has been intensively tested and stepwisely optimised. A description of the testing plant can be found in section 3.1.

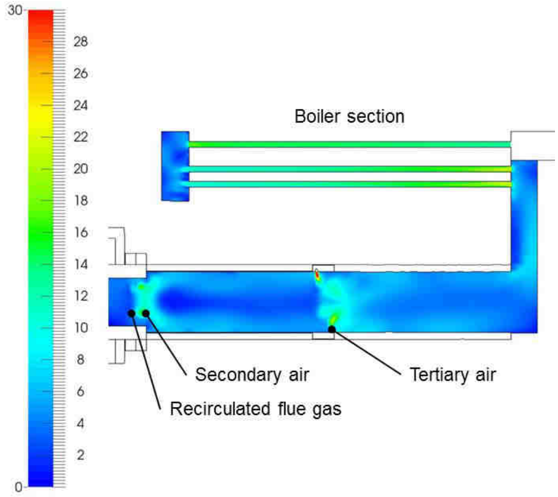

Figure 9: Design of the two-stage gas burner – mixture of combustion air with flue gas
Explanations: Isosurfaces of flue gas and air velocities [m/s] in the vertical cross-section of the combustion chamber; fuel: wood chips (fuel moisture content 34 wt.% w.b.); boiler load: 400 kW

3 METHODOLOGY CONCERNING TEST RUNS AND ANALYSES

Comprehensive test runs with accompanying measurements and analyses have been performed to evaluate the performance of the new technology and to validate the additivation strategy. Based on the data and experiences gained from the test runs a technological assessment of the testing plant has been performed.

3.1 Testing plant

A scheme of the testing plant with a thermal capacity of 400 kW is shown in Figure 10. The plant is equipped with a screw feeder, a horizontally moving grate, an insulated fuel bed section coupled to the gas burner with separately controllable combustion air and recirculated flue gas supplies. The testing plant is equipped with a robust and water cooled moving grate in order to ensure discharge of possibly formed ash agglomerates. Primary air and recirculated flue gas are injected from the bottom below the grate, which is used as air distributor. The ash produced in the process falls through the grate and is discharged by means of a conveying screw.

The fuel bed section is coupled to the combustion chamber. Air staging is applied in order to reduce NO_x emissions in the flue gas. Thus, the combustion chamber is separated into two different reaction zones, a reducing and an oxidising zone. Secondary (reducing zone) and tertiary (oxidising zone) air are injected through radial air nozzles in order to provide efficient mixing of unburned flue gases with the combustion air for a complete burnout. Additionally, recirculated flue gas is injected into the reduction zone in order to control combustion temperatures.

The cylindrical combustion chamber is surrounded by the radiant boiler section. Downstream the combustion chamber the convective section of the warm water boiler is located.

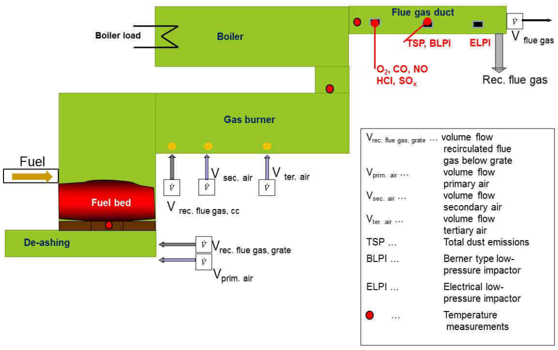

Figure 10: Scheme of the testing plant and the measurement set-up for test runs

3.2 Measurement and analyses methods applied

A significant number of different measurement and sampling technologies was applied in order to accurately evaluate the testing plant as well as to investigate the ash chemistry in the fuel bed (see Figure 10). To define the performance of the facility, characteristic process data such as air and flue gas flow rates, relevant temperatures as well as the boiler load were recorded continuously. Moreover, the flue gas composition downstream the boiler was continuously measured using standard flue gas analysers for O_2 (paramagnetic sensor), CO and NO (NDIR). Since no nameable OGC and very low PM emissions are expected, particle measurements have been performed in the undiluted flue gas. The total fly ash (TSP) concentrations (method according to VDI 2066) as well as the particle size distributions and concentrations of aerosols (particles <1 µm aerodynamic diameter, measurement with 9-stage Berner-type low-pressure impactors – BLPI and electrical low-pressure impactor - ELPI) have been repeatedly determined. During the test runs fuel and ash samples have been repeatedly collected and subsequently analysed regarding all relevant ash forming elements as well as carbonaceous species.

The moisture content of fuel samples has been determined according to ÖNORM EN ISO 18134-1: 2015 12 15 (determination of the weight loss during drying at 105°C until a constant weight is reached). The ash content has been determined according to ÖNORM EN ISO 18122: 2016 02 15 by determination of the loss of ignition at 550°C. C, H and N contents have been analyzed according to ÖNORM EN ISO 16948: 2015 07 15 (combustion and subsequent gas-phase chromatographical separation and measurement in an elemental analyser). The determination of Cl has been done according to ÖNORM EN ISO 16994: 2016 11 01 applying a digestion step based on bomb combustion in oxygen and absorption in NaOH (0.05 molar) followed by a measurement by ion chromatography. For the determination of the contents of major and minor ash forming elements (excluding Cl) as well as S a multi-step pressurised digestion with HNO_3(65%)/HF(40%)/H_3BO_3 followed by measurement by inductively coupled plasma optical emission spectroscopy (ICPOES) or inductively coupled plasma mass emission spectroscopy (ICPMS) (depending on detection limits) has been performed.

The determination of the TOC and TIC contents of the grate ash has been carried out according to ÖNORM EN 13137. For the TIC (total inorganic carbon) an aliquot is treated with acid, the generated CO_2 is measured by IR. The measurement instrument is calibrated with $CaCO_3$.The total organic carbon (TOC) is determined by the amount of total carbon (determined by an element analyzer) minus the TIC.

The analyses regarding the OC, EC, and CC contents of fly ash samples have been carried out with a carbon/hydrogen analyzer (Leco RC-612). The sample is inserted into a quartz tube and heated to defined temperatures. Carbon containing compounds released from the sample are oxidized to carbon dioxide, which is selectively detected by infrared cells. By choosing appropriate temperatures and carrier gases in the quartz tube total carbon (TC) as well as the fractions of organic carbon (OC), elemental carbon (EC) and carbonate carbon (CC) can be distinguished. Carbon released in a temperature window from 200 to 600°C under inert atmosphere is assigned to organic carbon, carbon released between 600 and 900°C is assigned to carbonate carbon, carbon detected after switching to oxidizing conditions to elemental carbon.

The data gained from the test runs have been evaluated regarding emissions, slagging tendencies and general aspects of plant operation. Additionally, mass, energy and element balances for selected test runs have been calculated to evaluate release ratios for ash forming elements, especially for K (see section 4.2).

3.3 Performance of test runs

Comprehensive test runs with accompanying measurements and analyses have been performed at the testing plant in order to evaluate the performance of the new technology in terms of operation behavior and emissions and to validate the additivation strategy. Test runs at nominal and at partial load (25% load) have been executed with conventional wood chips in order to optimise the operation and combustion conditions. As soon as stable operation of the plant could be achieved dedicated test runs with selected agricultural fuels have been performed. Particularly, the following fuels have been tested:

- agropellets (miscanthus pellets without kaolin)
- wheat straw pellets with 4 wt.% kaolin
- sunflower husk pellets
- miscanthus pellets with 2 wt.% kaolin

4 PERFORMANCE OF THE FUEL FLEXIBLE AND LOW-EMISSION COMBUSTION TECHNOLOGY

With each agricultural fuel representative three-day constant load operation tests were performed. The test runs should provide data and experiences regarding the influences of bed cooling and fuel additivation on the process, detailed balances for ash forming elements (especially K) over the fuel bed as a basis for the determination of ash transformation processes and K embedding in the bottom ash, regarding ash melting related problems, regarding the formulation of proposals for the definition of fuel-additive-mixtures and comprehensive data regarding the flue gas composition.

Therefore, the following parameters have been investigated

- General operation behaviour of the testing plant during operation with the different fuels
- Fuel bed temperatures
- Particulate emissions (TSP – total suspended particulate matter and PM_1 – particulate matter

smaller than 1 µm aerodynamic diameter)

- SO_x and HCl contents of the flue gas
- Fuel, ash, fly ash and (if occurring) slag compositions

4.1 Results of test runs performed

For all fuels tested stable load operation of the testing plant at 200 kW boiler output could be achieved. In Figure 11 the emissions trends regarding CO and NO_x as well as the particulate emissions are presented. In general, the testing plant showed a very stable operating behavior for all fuels tested indicated by a high burnout quality of the flue gases and by very low particulate emissions.

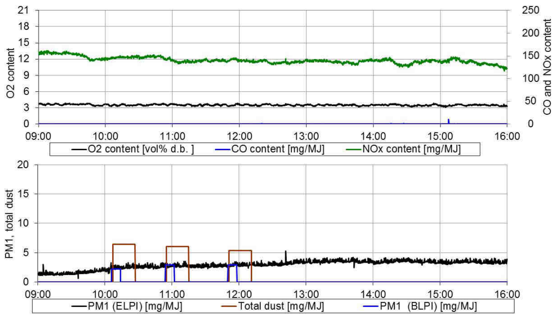

Figure 11: Trend of the O_2, CO and NO_x contents in the flue gas as well as of particulate emissions during a test run with wheat straw pellets with kaolin
Explanations: fuel: wheat straw pellets with 4 wt.% kaolin; emissions related to the NCV of the fuel; BLPI … Berner-type low-pressure impactor; ELPI … electric low pressure impactor

The average CO emissions amounted to values below 5 mg/MJ (related to the NCV of the fuel). The oxygen content of the flue gas was on average 3.5 vol% (d.b.). Therefore, it can be concluded that constant operation at very good burnout conditions of the flue gas could be achieved. Analyses of TSP and BLPI samples show that during stable operation conditions a very good gas phase burnout quality could be achieved indicated by low contents of condensable organic and soot particles in the flue gas (see also Table III). Furthermore, the NO_x emissions amounted to approx. 140 mg/MJ (related to the NCV of the fuel) and are on a low level considering the elevated N content of wheat straw (0.69 wt.% d.b.) due to optimised air staging in the gas burner.

Due to flue gas recirculation, the grate temperatures could be kept below 900°C for the entire test run time as shown in Figure 12. The relatively low fuel bed temperatures above the grate result from the build-up of an ash bed above the grate due to the high ash content of the fuel (9.5 wt% d.b.).

Regarding the particulate emissions, average PM_1 emissions of 3 mg/MJ were measured with the ELPI and the total dust emissions amounted to 6 mg/MJ on average (all data related to the NCV of the fuel). Considering the very high K-content of the fuel (about 8,400 mg/kg d.b. with additivation) these particulate matter emissions have to be assessed as very low. Conventional combustion systems emit PM_1 particles in the range of 120 mg/MJ when using a fuel with this amount of K (as shown in Figure 13).

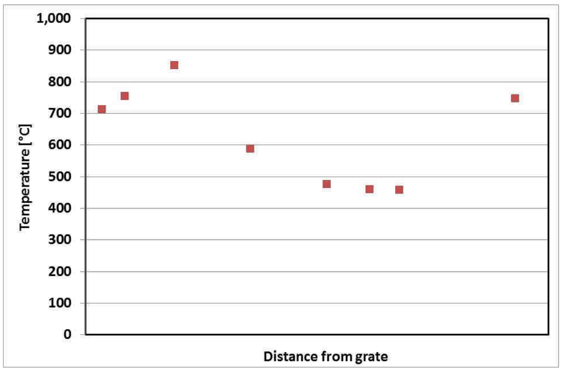

Figure 12: Temperature profile of the fuel bed during a test run with wheat straw pellets and kaolin
Explanations: fuel: wheat straw pellets with 4 wt.% kaolin; fuel bed temperatures measured discontinuously in vertical centre of fuel bed with Type-K thermocouple

The high K-retention capability of the fuel bed is also confirmed by element balances calculated over the plant, which show a K-release of less than 1 wt.% (d.b.). This clearly shows that besides the additivation with kaolin a well-defined combination of air staging and temperature control by flue gas recirculation below the grate (and grate cooling) contributes to a minimisation of the K release and the particulate emissions.

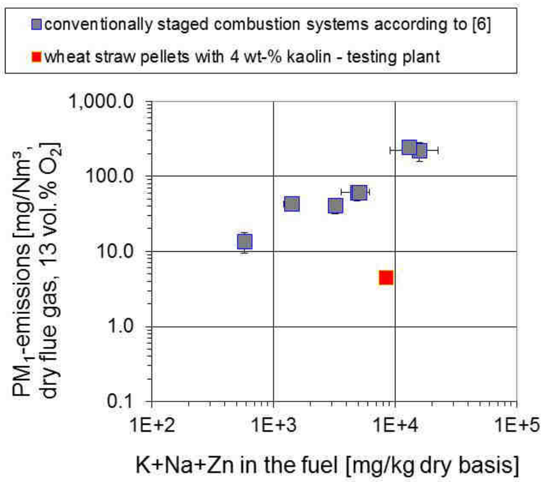

Figure 13: Correlation between the concentrations of aerosol forming elements in the fuel (K, Na, and Zn) and aerosol emissions downstream the testing plant
Explanations: fuel: wheat straw pellets with 4 wt.% kaolin; aerosol emissions (PM_1) of the testing plant measured with BLPI; emissions related to NCV of the fuel

In Figure 14 a picture of the grate ashes is presented. The ash is white and grey with some black (poorly burned) pellets. The ashes remain in pellet shape but the pellets can be easily destroyed. Some loosely sintered particles but no molten ash agglomerates were found. From the test runs with the testing plant it could be concluded, that a mixture of wheat straw and kaolin (about 4 wt.% kaolin content) could successfully be utilised and stable operation could be achieved. No problems with ash melting and, under consideration of the extremely high K content of the wheat straw, very low particulate matter emissions could be shown. The test run confirmed that additivation with kaolin represents an appropriate tool to further extend the fuel flexibility of the new technology.

Figure 14: Pictures of the grate and ashes from the test run with wheat straw and kaolin
Explanations: fuel: wheat straw pellets with 4 wt% kaolin; operation time: 130 h
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In general, the testing plant showed a very stable operating behavior for all fuels tested indicated by a high burnout quality of the flue gases and by very low particulate emissions. For all fuels tested it could be shown, that the new fuel flexible and low-emission combustion technology reaches total dust emissions below 15 mg/MJ and CO emissions of below 5 mg/MJ. In Figure 15 relevant results of the test runs performed in comparison to relevant Austrian and European emission limits are summarized.

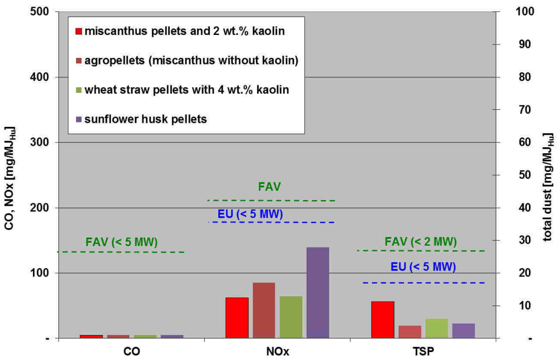

Figure 15: Emission of the testing plant in comparison to relevant emission limits
Explanations: emission limits according to „Feuerungsanlagen-Verordnung"(FAV, Austria) and EU-Directive 2015/2193 („Medium Combustion Plants Directive") valid for straw and other herbaceous fuels (grains, grasses, miscanthus); emissions related to the NCV of the fuel

No ash melting could be observed during the test runs with the other fuels. Only some ash agglomerates and small pieces of solidified slag could be found in the grate ash during the operation with agropellets. Flue gas recirculation has turned out to be an efficient tool to reduce the temperatures in the grate-near fuel bed zone and thereby to avoid ash melting.

Concluding, it could be shown that with the technological approach of fuel additivation combined with combustion related primary measures, a stable operation of the testing plant with very low emissions when utilising agricultural fuels is possible without need of cost intensive secondary measures to keep strict emission limits.

4.2 Chemical analyses and element balances

During the test runs performed with the testing plant fuel as well as grate and fly ash (TSP) samples have repeatedly been collected and subsequently analysed regarding relevant ash forming elements as well as carbonaceous species. The data gained from the test runs have been evaluated regarding emissions, slagging tendencies and general aspects of plant operation. Additionally, mass, energy and element balances over the testing facility have been calculated in order to evaluate release ratios for ash forming elements, especially for K.

In Table III the chemical compositions of samples derived from a representative test run with straw pellets with 4 wt% kaolin at stable load (200 kW) are presented.

Table III: Chemical compositions of fuel as well as grate and fly ash (TSP) samples
Explanations: TSP … total suspended particles; TIC … Total inorganic carbon; OC … organic carbon; EC … elemental carbon (soot) d.b. … dry basis; n.a. … not analysed

		straw pellets + kaolin (4 wt.%)	grate ash	TSP
Si	mg/kg d.b	20,800	163,000	
S	mg/kg d.b	1,160	2,800	76,500
Cl	mg/kg d.b	1,140	570	123,000
Ca	mg/kg d.b	5,840	44,900	13,300
Mg	mg/kg d.b	585	4,800	2,130
K	mg/kg d.b	8,400	70,300	284,000
Zn	mg/kg d.b.	7	45	4,130
Al	mg/kg d.b.	9420	92,700	17,600
TIC (ash)	mg/kg d.b.		<1,000	<1,000
TOC/OC	mg/kg d.b.			50,000
EC	mg/kg d.b.			33,500

The test run fuel shows a typical composition for wheat straw. The grate ash is dominated by Si and K and contains a low carbonate content indicated by the low TIC content. K is mainly bound in silicates which are thermodynamically quite stable. The fly ash is dominated by K-sulphates and K-chlorides and shows a good burnout quality indicated by low contents of condensable organic (5 wt.% d.b.) and soot particles (3.4 wt.% d.b.). The mass and elemental balances performed for the other fuels tested show similar results and also show a very efficient embedding of K the grate ash (mainly as silicates and as carbonates to some extent.

Based on the analyses performed element balances over the testing facility have been calculated in order to evaluate the release ratios for Ca, K and Zn. As shown in Figure 16 less than 1 wt% of the amount of K and only about 8 wt% of the amount of Zn in the fuel are released to the flue gas as particulate emissions, indicating an efficient embedding of these elements in the grate ash.

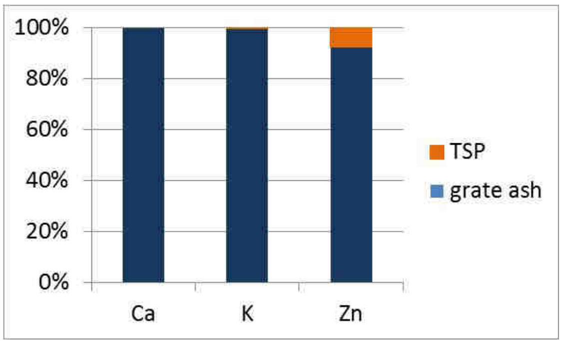

Figure 16: Distribution of Ca, K and Zn
Explanations: results of a test run at the testing plant with wheat straw pellets with 4 wt.% kaolin; TSP … total suspended particles

5 SUMMARY AND CONCLUSIONS

The demand for wood fuels for biomass heating and CHP plants is steadily increasing, thus the prices also rise accordingly, which results for more and more plant owners in economic problems. The utilisation of non-wood biomass fuels would be a possible alternative, but due to ash-related problems these fuels cannot be used in conventional biomass heating systems designed for wood fuels so far. Within a nationally funded Austrian research project a new, fuel flexible and low-emission combustion technology in the power range from 300 to 1,000 kWth for ash-rich fuels with low ash melting temperatures (non-wood biomass fuels) has been developed. In a first step fundamental research on emission formation, especially on PM emission formation, as well as research regarding the ash-melting behaviour of non-wood biomass fuels and the embedding of condensed alkaline metals in the grate ash under consideration of additive utilisation with accompanying thermodynamic high-temperature equilibrium calculations (TEC) for the prediction of the behaviour of ash forming elements was performed. A number of feasible concepts were carefully evaluated and finally a concept based on extremely staged combustion coupled with novel bed cooling measures turned out to be the most promising approach.

In a next step, basic concepts for the fuel bed section and the gas burner were developed and evaluated by means of simulation codes for biomass conversion to design the fuel bed section and by means of CFD simulations of the gas burner to enable an almost complete burnout and therefore low CO, OGC and organic PM emissions at low excess air. Based on the concepts developed a testing plant with a thermal capacity of 400 kW has been designed and manufactured and then intensively tested and stepwisely optimised.

Comprehensive test runs with accompanying measurements and analyses have been performed with diffenrent agricultural fuels to evaluate the performance of the testing plant and to validate the additivation strategy. Based on the data and experiences gained from the test runs a technological assessment of the testing plant has been performed. Test run results show that a stable operation of the testing plant with very low emissions compared to state-of-the-art grate-fired systems is possible. For all fuels tested the new fuel flexible and low-emission combustion technology reaches total dust emissions below 15 mg/MJ and CO emissions of below 5 mg/MJ. With e.g. kaolin addition the ash melting temperature can be significantly increased, which is also confirmed by the results of TEC and the test runs. Besides the additivation with kaolin a well-defined combination of air staging and temperature control by flue gas recirculation below the grate (and grate cooling) contributes to a minimisation of the K release (efficient embedding in the grate ash) and the particulate emissions.

It could be shown that with the technological approach of fuel additivation combined with combustion related primary measures (air staging and bed cooling), a stable operation with very low emissions when utilising agricultural fuels is possible without need of cost intensive secondary measures to keep strict emission limits. With this technological approach additional fuel assortments (non-wood biomass fuels) may be utilised in an economically competitive way, which enlarges the available biomass fuel potential and increases the flexibility for the user.

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