



Guidelines for advanced fuel and boiler design



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Preface

The project *BIOFLEX!* (Clean and flexible use of new difficult biomass fuels in small to mediumscale combustion) has been supported by ERA-NET Bioenergy under its 9th Joint Call for Research and Development in the period between 01/01/2016 and 31/03/2019. ERA-NET Bioenergy is a network of national research and development programmes focusing on bioenergy. Within the 9th Joint Call for Research and Development six countries participated in this coordinated activity: Austria, Germany, the Netherlands, Poland, Switzerland, Sweden and the United Kingdom. The mission of ERA-NET Bioenergy is to enhance the quality and cost-effectiveness of European bioenergy research programmes, through coordination and cooperation between EU Member States.

Small (<500 kWth) to medium scale (0.5-10 MWth) combustion plants are destined to grow in importance in a future decentralised, sustainable European energy supply scenario. The flexible utilisation of new, "challenging" biomass fuels in these plants is one of the major challenges for the coming years. While large-scale plants have become individually tailored to cheaper, low-grade fuels, small-scale applications today rely on chemically untreated stem wood fuels (log wood, wood chips, wood pellets) and medium-scale applications additionally on selected cheaper assortments such as forest residues as well as waste wood. Other resource efficient fuels like wood from short rotation forestry (SRF – e.g. poplar and willow), herbaceous fuels (e.g. straw) as well as residues from agriculture and industry (shells, kernels, sludges etc.), however, inevitably gain importance also for these applications. However, due to their chemical composition, these fuels are challenging in terms of combustion behaviour and emissions. Increased S, CI and N contents lead to increased gaseous HCI, SO_x and NO_x emissions. Elevated ash contents with high levels of e.g. K, Si and P cause problems with slagging, deposit formation and fine particulate emissions, of which especially the latter is growing in relevance with the EU-Ecodesign directive (relevant for small-scale plants) and the Medium Combustion Plant (MCP) directive. However, in small-scale combustion, individually tailored solutions and expensive secondary measures for emission reduction are economically not viable and for medium-scale plants limited knowledge regarding the problems associated to the utilisation of "challenging" biomass fuels so far held back the development of Flexi-fuel combustion systems, leaving this market sector almost unexploited. Therefore, the development of cost efficient and general primary concepts for increased fuel flexibility is urged in order to boost the innovation, enlarge market potential and deliver clean and efficient technology solutions.

Against this background the overall objective of *BIOFLEX!* was to increase fuel flexibility in the small to medium-scale heat and power production sector towards more challenging solid biomass fuels that do not compete with food production. This should be reached by further development and implementation of fuel design and combustion system design related measures enabling clean and efficient utilisation of bio-residues, by-products and other resource efficient energy crops at low emissions, high efficiencies and high availabilities. Therefore, the project focused on the following objectives:

• To improve the understanding of ash transformation issues in combustion by fundamental ash transformation research and by connecting ash transformation with the combustion.





- To investigate the application of additives and fuel blending in order to make new problematic feedstock better applicable in small to medium-scale biomass combustion systems.
- To further develop combustion technologies for the small (<500 kW_{th}) and the medium (0.5 – 10 MW_{th}) capacity range by means of primary measures.
- To perform testing of these measures in appropriately adapted testing plants in cooperation with furnace and boiler manufacturers.
- To develop guidelines for the design of appropriate low emission combustion technologies and for appropriate fuel design of the identified fuels.

In order to reach these objectives, a consortium of 7 research partners and 5 industrial partners from 4 European countries collaborated within *BIOFLEX!* (see next page).

This document summarizes the outcomes of the investigations regarding the design of appropriate low emission small and medium-scale combustion technologies and regarding appropriate fuel design strategies, i.e. the utilisation of fuel additives and the application of fuel blending in order to broaden the range of applicable biomass fuels. With its recommendations which have been derived based on scientific investigations as well as comprehensive test runs at small-scale and pilot-scale combustion plants it should support furnace and boiler manufacturers as well as biomass fuel producers and traders concerning the optimization of their products and the development and design of new products. Moreover, these guidelines shall provide information for plant operators regarding the risks and opportunities of the utilisation of so-called challenging biomass fuels.

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1 Introduction and objectives

The overall objective of the ERA-NET Bioenergy project *BIOFLEX!* was to perform research and development work to increase fuel flexibility in small (<500 kW_{th}) and medium-scale ((0.5 to 10 MW_{th}) biomass combustion plants towards the use of more challenging solid biomass fuels such as wood fuels from short rotation coppice (SRC) and agricultural residues (e.g. straw, grass). When applied in conventional fixed-bed combustion systems, which were initially designed for wood fuels, these fuel assortments are well known to cause problems with gaseous and particulate emissions as well as ash melting (slagging).

In order to make current state-of-the-art combustion systems suitable for an utilisation of these fuels the project followed two main strategies. The first strategy was related to investigations regarding the application of fuel blending and utilisation of inorganic fuel additives with the main focus to better control problems with ash melting and to reduce fine particulate emissions. This strategy is in the following referred to as "*fuel design*". The second strategy aimed at further development of existing wood combustion technologies in the small and medium-scale capacity range to enhance their fuel flexibility towards challenging fuels with elevated particulate emissions as well as low ash melting temperatures. Therefore, preliminary primary measures should be appropriately implemented into the furnace concepts.

To achieve these aims, fundamental lab-scale studies, simulation model development, CFD simulation based design studies as well as test runs at conventional and appropriately modified small and medium-scale biomass combustion plants were performed. In these guidelines the results of the *BIOFLEX!* project related to the work on fuel design and combustion technology development are summarised in a way that they become broadly applicable. Furnace and boiler manufacturers, operators of biomass combustion plants as well as biomass fuel producers and traders are therefore the target groups which shall benefit from the project results via these guidelines.

In the first part of the guidelines (section 2), the impact of different fuel properties on the combustion process is discussed to improve the basic understanding for the aspects concerned. Based on this discussion so-called "challenging" biomass fuels are identified and characterised with respect to their combustion related crucial properties, and the overall approach followed within *BIOFLEX!* is introduced (section 3).

Subsequently in section 4, different ash chemical and fuel design related aspects concerning a deliberate fuel manipulation towards high-performance non-woody fuel application are elaborated. Particular focus is here set on using fuel additives based on clay minerals (kaolin) and existing examples of successful applications. Different technological aspects and calculation procedures for dosage of added kaolin are presented as this mineral additive had intensively been investigated in the *BIOFLEX!* project and seems interesting in terms of the reduction of particulate emissions and slagging problems.

Finally, in section 5, technical and operational measures to create a furnace, which can cope with challenging fuels, are presented. This requires a deeper view on how to generally handle fuels with elevated fuel ash content (e.g. grate design, avoidance of ash melting by temperature control or advanced air staging and flue gas recirculation below the grate, robust





layout of de-ashing systems, automatic boiler cleaning, etc.). In particular, fuels with a high potassium, chlorine and silicon content are regarded, as they pose specific risks for slagging, deposits and aerosol formation. Distinction is made between small-scale boilers and medium-scale appliances. Several relevant options are presented and evaluated, such as geometric design concepts, air staging concepts, CFD-based optimization, combustion control strategies as well as secondary measures for PM-, NO_x- HCI- and SO_x-emission abatement are addressed.

2 Impact of fuel quality on the combustion process

2.1 Parameters influencing combustion performance - overview

The chemical composition of biomass fuels can vary concerning the concentrations of the main elements (C, H, O, N), sulphur and chlorine as well as of the ash content respectively the concentrations of ash-forming elements. In the following the impact of the most relevant parameters on furnace and boiler operation are briefly summarised.

In general, the C, H and O contents as well as the ash content determine the **gross calorific value (GCV)** of a biomass fuel. The **moisture content**, **the H-content and the GCV** determine the **net calorific value (NCV)**, the most relevant parameter for utilisation in a combustion plant. The moisture content however, also significantly influences the storability and energy density of a biomass fuel.

Besides its influence on the GCV, the **ash content** has to be considered concerning the deashing system, ash storage, ash utilisation, the grate design as well as the fact that high ash contents lead to higher entrainment of ash particles from the fuel bed with the flue gas and consequently to increased deposit formation, erosion and particulate matter emissions. Therefore, the ash content is an important parameter to be regarded during plant design.

The **ash melting behaviour** of biomass ashes is characterized by the chemical composition. In general, problematic ash melting in biomass combustion is related to the formation of low-temperature melting compounds of different alkali (K+Na) silicates, phosphates and/or chlorides. With increasing contents of Ca, Mg and Al less problems with ash melting usually occur. The ash melting behaviour affects the combustion technology and the process control system and is an important factor concerning slagging, deposit formation and operational safety.

Bulk density and especially the **energy density** (=bulk density * NCV) of the fuel have also to be considered concerning fuel transport, storage, and feeding systems. In this respect pelletized biomass fuels show clear advantages compared to non-densified materials due to their higher bulk and energy density. The **amount of fines** is relevant concerning the appropriate selection of the combustion technology and the process control. Regarding small-scale systems, the amount of fines is also of big relevance concerning the fuel feeding system (e.g. this is a quality parameter for pellets). The amount of fines is an important factor regarding particle entrainment (i.e. they can cause strain formation, elevated fly ash emissions and incomplete burnout).





The **N** content is of special relevance concerning NO_x emissions. Although with increasing N-content of the fuel the conversion rate to NO_x decreases, the absolute NO_x emissions increase.

S and **CI** are relevant elements concerning gaseous emissions (SO_x, HCI), fine particle (aerosol) formation as well as ash deposit formation on boiler tube surfaces. Ash deposits are mainly formed by alkali metal salts such as K_2SO_4 and KCI. High CI-contents of the fuel therefore also increase corrosion related problems especially due to ash deposits with high CI-contents. Moreover, CI reduces the ash melting temperature of deposits. Due to these deposit formation and corrosion related issues, significant impact of the S- and CI-contents on high-temperature corrosion of heat exchanger surfaces (most relevant for superheaters in steam boilers) is given. Furthermore, it has to be taken into account, that increasing S and CI concentrations in the flue gas also shows impacts on low-temperature corrosion in boilers, economisers, filters and air pre-heaters, either by acid dew point corrosion or by formation of corrosive hygroscopic salts.

Regarding the utilisation of so-called "difficult" biomass fuels, **ash formation processes** and **ash related problems** are of major relevance. For a better understanding of the terminology applied in this document, a brief overview regarding ash formation in fixed-bed biomass combustion processes is given in the following. In fixed-bed combustion processes several ash fractions occur which are usually categorised as follows.

Grate ashes are solid residues from the combustion process, which have to be removed from the grate after conversion of the volatile matter and charcoal combustion. They mainly consist of oxides, sulphates, carbonates, silicates and phosphates of refractory elements such as Ca, Mg, Al and Fe, as well as of the more semi-volatile species K and Na. Moreover, they contain minor amounts of heavy metals. Depending on the charcoal burnout quality they may also contain certain amounts of organic carbon.

Coarse fly ashes are formed by fuel, charcoal and ash particles entrained from the fuel bed with the flue gas and typically have particle sizes between 1 and some 100 μ m. The amount of coarse fly ashes formed depends on the ash content of the fuel, the amount of fines in the fuel and on the gas velocities in the region near the grate. The main constituents of coarse fly ash are about the same as those of grate ash, however, they may also contain a certain amount of carbonaceous species (e.g. entrained charcoal particles). Coarse fly ash contributes to deposit formation in the furnace and the boiler as well as to particulate matter emissions.

Fine particulate matter (particles smaller than 1 μ m) is formed from volatile and semi-volatile species released from the fuel bed into the gas phase. Consequently, the chemical composition of the fuel, respectively the release behaviour of the elements concerned, plays a determining role. Regarding chemically untreated biomass fuels, K is the most relevant element regarding the formation of fine particulate matter, however, also S, Cl, Na, P and easily volatile heavy metals such as Zn and Pb provide contributions. This is also illustrated by Figure 1, which shows - based on database values from combustion tests - the dependency of the fine particulate matter emissions (PM₁ = particulate matter smaller than 1 μ m) downstream the boiler and upstream any particle precipitation device on the K, Na, Zn and Pb content in the fuel.







Figure 1: PM₁ emissions as a function of the concentration of aerosol-forming species (K + Na + Zn + Pb) in the fuel [1]

In the gas phase these species undergo reactions and later, when the gas is cooled down, they are subjected to gas-to-particle conversion processes (nucleation, condensation). The composition of the resulting solid compounds as well as the position in the plant, where these gas-to-particle conversion processes occur, depend on the species released from the fuel bed and the profile of the temperatures and gas-phase atmospheres (reducing, oxidising) along the pathway of the flue gas through the plant (combustion chambers, heat exchangers). For chemically untreated biomass fuels, K, S and Cl are the elements mainly determining these processes. Regarding agricultural fuels also P-compounds may contribute to fine particulate matter formation. Minor contributions come from easily volatile heavy metals such as Zn and Pb. Depending on the gas phase burnout quality achieved during the combustion of the combustible gases released from the fuel bed, this fraction may also contain certain amounts of elemental carbon (soot = EC) and organic carbon components (OC). Fine particulate matter contributes to deposit formation in boilers and to the dust emissions (fine particulate emissions). Moreover, especially for K and Cl rich fuels, the formation of KCl-rich deposits may cause boiler tube corrosion, especially in steam boilers.

The fractionation into grate ashes, coarse fly ashes and fine particulate emissions partly depends on the plant design (e.g. grate area, air staging) and to a relevant extent also on the contents of easily volatile, semi-volatile and non-volatile ash forming elements in the fuel. However, in conventional small-scale biomass boilers the grate ash usually amounts up to 90 w% of the total ashes formed, while in medium-scale fixed bed combustion plants the amount of fly ashes may increase up to 40 wt%, which is mainly due to the higher gas velocities in the region near the grate prevailing in medium-scale combustion plants. Consequently, regarding the fly ash emissions, about 90 % of the fly ashes in small-scale appliances are fine particulate matter emissions while in medium-scale combustion plants typically the contribution of coarse fly ashes to the total fly ash emissions, this is due to higher particle entrainment from the grate.





2.2 Properties that define challenging biomass fuels

Widening the feedstock range of small and medium-scale biomass furnaces towards agricultural fuels and biomass residues is associated with a number of operational and plant design related problems which are related to the different chemical compositions of these fuels. Within the *BIOFLEX!* project, the utilisation of biomass assortments which are typical for these fuel types has been investigated. These so-called challenging fuels investigated were poplar (from short rotation forestry), wheat straw, grass and sunflower husks. With these fuels a broad range of different chemical compositions are covered, and based on the chemical analyses of these fuels it is also explained in the following, why they are assessed as challenging regarding their utilisation in conventional combustion plants which are designed for wood fuels.

In Table 1, some relevant parameters of the fuels investigated within the project are presented based on analyses data from single samples gained from the project. Comparison with database values prove that the fuel samples analysed are typical for the respective fuel assortment. Additionally, two fuel indices are mentioned which can be used for a preliminary assessment regarding ash melting properties and potentials for fine particulate emissions. To highlight relevant critical fuel properties, the "challenging" biomass fuels are in the following assessed by comparing to typical wood pellets which comply with requirements according to EN 17225-2, class A1.

		Wood pellets *)	Wheat straw pellets	Sunflower husk pellets	Grass pellets	Poplar pellets
Moisture content	wt% w.b.	5.5	8.5	6.9	9.7	7.9
Ash content	wt% d.b.	0.34	4.3	2.9	8.5	2.2
С	wt% d.b.	50.7	47.5	51.3	45.4	49.5
Н	wt% d.b.	6.1	5.8	6.3	5.8	6.0
Ν	wt% d.b.	<0.1	0.44	0.65	2.5	0.27
S	mg/kg d.b.	52.1	717	1,490	2,260	384.0
CI	mg/kg d.b.	64.3	2,090	383.0	3,600	75.0
Са	mg/kg d.b.	811	2,860	3,810	7,560	6,010
Si	mg/kg d.b.	166.0	9,460	490.0	9,630	211.0
Mg	mg/kg d.b.	131.0	767	1,910	3,350	554
Al	mg/kg d.b.	25.1	145.0	27.8	988	31.2
Na	mg/kg d.b.	14.6	42.1	6.4	369.0	19.9
К	mg/kg d.b.	414.0	8,450	7,450	21,200	3,070
Fe	mg/kg d.b.	27.5	117.0	83.2	721	55.4
Ρ	mg/kg d.b.	54.7	638	752	3,610	873
Zn	mg/kg d.b.	9.0	6.8	14.5	28.1	42.3
Gross calorific value	kJ/kg d.b.	20,080	18,880	20,200	18,350	19,600
Fuel indexes						
K+Na+Zn	mg/kg d.b.	437.6	8,499	7,471	21,597	3,132
(Si+P+K)/(Ca+Mg+Al)	mol/mol	0.69	5.3	1.33	2.8	0.66

Table 1: Relevant parameters of the fuels investigated within the *BIOFLEX!* project

Explanations: w.b. ... wet basis; d.b. ... dry basis; *) wood pellets according to EN 17225-2, class A1

Compared to wood pellets, the C and H contents as well as the gross calorific values of wheat straw pellets, grass pellets and poplar pellets are slightly lower while for sunflower husk pellets





they are slightly higher. The N-content increases from wood pellets over poplar, wheat straw and sunflower husks to grass pellets, and therefore also increasing NO_x emissions have to be expected in this order.

Regarding the S content, all fuels show significantly higher values compared to wood pellets. They increase from poplar over wheat straw and sunflower husks to grass pellets. While the CI content of poplar pellets is well comparable to regular A1-wood pellets, sunflower husk pellets show a slightly increased CI content. The CI content of wheat straw and grass pellets are significantly higher (35 and 60 times the CI content of wood pellets, respectively).

All fuel assortments show, compared with wood pellets, significantly increased ash contents, rising from poplar over sunflower husks and wheat straw to grass pellets, which show the highest ash content (8.5 wt% d.b). From the comparison of the most relevant ash forming elements it can be concluded that ashes which are formed during poplar and sunflower husk combustion are dominated by Ca, K and Mg. Grass and wheat straw pellets, however, contain much more Si and also high amounts of K which have a significant impact on the ash melting behaviour. The molar ratio of (Si+P+K)/(Ca+Mg+Al) can be used as a first preliminary indicator to assess the melting behaviour of biomass ashes [1]. In Figure 2 database values showing the trend of decreasing ash melting temperatures with an increasing value of this fuel index are presented. Poplar pellets with a very low value of 0.66 and sunflower husk pellets (1.33) are expected to be non-problematic while ash melting and slagging related problems are expected to increase during combustion of grass pellets (index value of 2.8) and especially of wheat straw pellets (index value of 5.3).



Figure 2: Shrinkage-starting temperature versus the molar ratio of (Si + P + K)/(Ca + Mg)

As mentioned before, semi-volatile elements (K, Na) and easily volatile heavy metals (Zn) provide major contributions to the formation of fine particulate emissions. This is reflected by the fuel index K+Na+Zn+Pb (see Figure 1). There is a trend of increasing fine particulate emissions with increasing value of this index [1]. As it can be revealed from Table 1, for chemically untreated biomass fuels the index is strongly dominated by the K content and due to the very low Pb contents, the fuel index has been reduced to K+Na+Zn. However, the potential for fine particulate emissions significantly increases from wood pellets over poplar, sunflower husks and wheat straw to grass pellets, which show a 50-fold value of softwood pellets. Accordingly, when considering the data in Figure 1, the potential for fine particulate matter emissions is increased by the factor of 20 when comparing wood pellets and sunflower husk pellets.





Consequently, the most relevant combustion related issues which have to be considered regarding the utilisation of the fuels mentioned are increased NO_x emissions, ash melting, fine particulate emissions and risks related to high and low temperature corrosion.

3 Approach for the utilization of challenging biomass fuels

Regarding the approach for implementing measures to improve fuel flexibility it has in general to be distinguished between small-scale and medium-scale combustion systems. Small-scale combustion systems are typically produced as serial products. Consequently, the implementation of combustion technology related optimisation measures is restricted by the specific framework conditions of the underlying concepts with regard to furnace geometries and combustion technologies applied. Significant changes can usually only be implemented in newly developed product series. Hence, especially for small-scale applications, the fuel design strategy developed within *BIOFLEX!* can significantly broaden the range of applicable feedstocks since it aims at positively influencing crucial fuel properties by the targeted addition of inorganic additives without any need for changes in the combustion technology.

Medium-scale combustion plants however are usually designed considering the framework conditions at a specific client. Consequently, it can be decided from case to case to which extent measures to improve fuel flexibility shall be implemented. Hence, when considering the guidelines for fuel flexible combustion technology design proposed in this report, a significant step towards higher fuel flexibility can be achieved. Of course the guidelines for fuel flexible furnace design can additionally be combined with the application of additivated fuels in order to further improve operation performance and reduce emissions.

Besides the development of fuel design strategies and guidelines for fuel flexible furnace and boiler concepts, *BIOFLEX!* focused on the commercial viability of the resulting measures. Therefore, all technologies developed within the project, have also been assessed in terms of their techno-economic performance. In this context it has to be emphasized that all measures proposed in this report have proven not only their technical applicability but also an acceptable economic performance. However, even though under the economic framework conditions assumed within *BIOFLEX!* generally positive results could be achieved, it is important to carefully evaluate the additional costs generated by specific measures for enhanced fuel flexibility and the cost savings achieved by the application of an in terms of combustion behaviour challenging but cheaper biomass feedstock.

4 Fuel design for use of challenging biomass fuels

4.1 Introduction to fuel design

4.1.1 The concept of fuel design

The term **fuel design** has more frequently been used in the literature during the last years, to describe the approach of using primary fuel based measures to increase the fuel quality and combustion performance in biomass combustion and gasification applications. While the conventional fuel indices available [e.g. 1, 3] may indicate potential ash and emission related effects during combustion of a fuel respectively fuel blend, the concept of fuel design implies a clearer strategy of actively changing the fuel ash composition and influence the system





towards a certain direction. This can preferably be implemented either by blending the primary fuel with a specific secondary fuel or by using a fuel additive, with the aim to achieve the desired effect. In this perspective, the concept of fuel design was developed and defined as a novel tool to design the ash and to reduce/avoid unfavourable ash chemical transformations and their related operational and emission effects in biomass combustion processes [4, 5]. The basis for applying this kind of fuel design concepts is to consider the composition of the fuels and additives involved, derived by proper and relevant fuel characterisation. The fuel composition should be viewed by its molar concentrations (mole/kg_{dry fuel}) of major ash forming elements (K, Na, Ca, Mg, Al, Si, P, S, and Cl) and some trace elements (e.g. Zn). The relative concentrations of these main ash forming elements are then considered in relation to fundamental ash chemistry (e.g. thermodynamic considerations, primary oxide stability, etc.), to assess and predict the major ash chemical behaviour of different fuels [6].

To further enable a prediction of the specific ash chemical reaction pathways and thereby also develop more generally applicable fuel design concepts, the main ash forming elements can initially be grouped as elements forming positively charged ions acting as Lewis acids (K, Na, Ca, Mg, Fe, Al) and negatively charged molecular (Si, P, S) or atomic ions (Cl) acting as Lewis bases during the ash transformation reactions in the combustion process [4]. This will enable a more reaction-based approach, which is lacking in conventional fuel indices and thermodynamic equilibrium models. This fuel design approach has for example been applied to guide the mixing strategy for co-combustion of seaweed with the energy crop Miscanthus [7]. As described by basic inorganic high-temperature chemical considerations, all major ash forming elements (except CI) are assumed to initially be oxidized in so-called "primary" ash transformation reactions. Furthermore, also subsequent secondary and tertiary ash transformation reactions occur to a large extent driven by the reaction routes of the different oxides formed and their transformation products. In addition, also different physical fuel and ash properties and combustion process related considerations need to be considered, to fully assess the potential real-life ash and emission related effects in different combustion plants [6]. To achieve this kind of complex assessment of the combustibility and performance of different fuels and the potentials with different fuel design concepts, simplified guidelines have to be developed.

Within the *BIOFLEX!* project, some fuel design concepts were therefore developed, applied and evaluated as novel tools to mitigate *slagging tendencies* and *fine particle emissions* during combustion of challenging biomass fuels in small and medium scale grate boilers and burners. Three different fuel design concepts were evaluated, i.e. *i*) fuel additivation with the mineral additive kaolin, *ii*) fuel blending with an ash rich biomass and sludge, and *iii*) fuel blending with the same ash rich biomass and pure softwood. In Figure 3, the concentrations of major ash forming elements for the studied fuels within *BIOFLEX!* are shown on a mole/kg_{fuel} basis, ordered according to their Lewis acid-base properties, i.e. the weakest Lewis acid forming element at the left and the weakest Lewis base forming element to the right. This enables a first assessment of potential ash and emission related effects, and forms the basis for defining suitable fuel design concepts. It is obvious from this graph that both the poplar and sunflower husk fuels have a surplus of e.g. K, Ca, and Mg, which will imply that oxides and carbonates of these element will dominate the ash, causing low slag formation and some fine particle emissions (caused by K release). On the opposite, both wheat straw and grass fuels have high





K/Ca ratios together with high Si and Cl contents and for grass also relatively high P and S concentrations. These fuels are therefore expected to cause severe slagging (silicate melts) as well as high fine particulate emissions from K-chlorides. Accordingly, the fuel design strategies to mitigate potential problems, needs to be adjusted from case to case.



Figure 3: Molar concentration of major ash forming elements ("fuel fingerprint") in the four biomass fuels studied within *BIOFLEX*!

4.1.2 Fuel blending

The use of fuel blending between ash rich "challenging" biomass can be an effective strategy as a primary measure to reduce ash related operational problems and particle emissions. Different concepts exist, e.g. biomass-biomass, biomass-peat, biomass-industrial residues/sludge, and biomass-coal [8]. Co-combustion of biomass with peat has, for example, shown significant potential for both, reduction of slagging tendencies and fine particulate matter (PM) emissions in grate fired systems. Recommendations for the selection of the peat type and the blending strategy have already been defined [9]. Furthermore, the potential use and positive effects by blending ash rich (e.g. high Si and K contents) biomass fuels with phosphorus rich sewage sludge have been studied for fluidized beds [10], although they are less explored for fixed-bed applications. However, a detailed understanding of the ash chemical mechanisms and suitability of different measures for different fuels as well as technological and economical aspects are still not fully elucidated, understood and demonstrated.

Within *BIOFLEX!*, the concept of blending wheat straw (high Si and K) with municipal sewage sludge (MSS) was studied, with respect to the influence on combustion performance, slag formation, gaseous and particulate emissions. In addition, combustion tests with blends of wheat straw with softwood were performed, mainly as a tool to "dilute" the ash content and





enable good combustion performance. These blending tests will not be further discussed in this guideline.

4.1.3 Fuel additives

The use of fuel additives can also be an effective measure to combat ash and emission related problems in biomass combustion applications. Fuel additives may either be mixed and introduced into the boiler together with the regular biomass fuel (e.g. for wood chips), or copelletized with the raw material into the produced pellet fuel. In both cases this can be done either via "dry" powder ad-mixing or via nozzle injections of a water slurry. Additive for combustion applications can be sorted into different types according to their composition, i.e. additives based on calcium, phosphorus, sulphur, aluminium and aluminium-silicates [8]. Calcium based additives (e.g. CaO, CaCO₃) may primarily be used to change the melting properties (increase the melting temperature) of the ash and reduce slagging tendencies in grate fired applications [11]. Further, the use of aluminium-silicates as additives during combustion of challenging biomass has been extensively discussed in the scientific literature. The most studied AI-silicate based additive in this context is probably the clay kaolin, consisting mainly of the mineral kaolinite [Al₂Si₂O₅(OH)₄]. Kaolin has been shown to have great potential for capturing alkali metals, especially potassium, and incorporate them into stable hightemperature melting Al-silicate phases. This effect can therefore both, reduce the release of fine particle and deposit forming alkali species from the fuel bed and at the same time reduce the melting and slag formation in grate boilers/burners [8].

Within *BIOFLEX!*, the main fuel design method applied and evaluated was therefore the use of the mineral additive kaolin for four ash rich challenging biomass fuels, i.e. poplar, wheat straw, grass and sunflower husks. In this work, the concept was further evaluated for different fuels in grate fired applications and, together with previous research and experiences, specific strategies and recommendations could be defined and published in this guideline.

4.2 Application of mineral fuel additives

4.2.1 Kaolin as fuel additive

As mentioned earlier, research has clearly shown that the mineral kaolinite in the kaolin clay is the relevant component. Alkali vapours react with the mineral and form solid products that do not melt at normal grate combustion temperatures such as leucite (KAISi₂O₆), kalsilite (KAISi₂O₄), microcline (KAISi₃O₈), or analogue compounds containing Na. Upon heating, kaolin undergoes transformations, where the first step is a dehydroxylation at around 450-600°C where the kaolinite loses water and transforms into meta-kaolin (Al₂O₃·2SiO₂), a type of amorphous aluminium silicate, that effectively reacts with gaseous alkali species [12]. Upon further heating, the meta-kaolin transforms to a spinel structure at 980°C and further to mullite at 1100°C, both different forms of Al-silicate that are assumed to capture alkali less effectively than meta-kaolin [13]. Thus, the efficiency of kaolin in capturing alkali metals may decrease at higher temperatures which are in a range that is relevant for the conditions on the grate in fixed bed boilers. When introducing a biomass ash, all ash and kaolin transformation details are not fully understood. However, the transformations of the kaolin and subsequent reactions between the meta-kaolinite and various gaseous alkali species (here as potassium





compounds) can be described by the following overall formulas [13] where (I) shows the transformation into meta-kaolinite, and II+III show reactions with KOH (g), while IV+V shows reactions with KCI (g).

$$Al_2Si_2O_5(OH)_4 \rightarrow Al_2O_3 \cdot 2SiO_2 + 2H_2O \tag{1}$$

$$Al_2O_3 \cdot 2SiO_2 + 2KOH \rightarrow 2KAISiO_4 + H_2O \tag{II}$$

$$Al_2O_3 \cdot 2SiO_2 + 2KOH + 2SiO_2 \rightarrow 2KAISi_2O_6 + H_2O \tag{III}$$

$$Al_2O_3 \cdot 2SiO_2 + 2KCI + H_2O \rightarrow 2KAISiO_4 + 2HCI$$
 (IV)

$$Al_2O_3 \cdot 2SiO_2 + 2SiO_2 + 2KCI + H_2O \rightarrow 2KAISi_2O_6 + 2HCI$$

$$(V)$$

The additive level is determined based on basic chemical calculations, earlier experiences and some additional considerations. In principal, and to start with, it can be assumed that there is a molar relation of 1:1 between alkali in the fuel $(K+Na)_{fuel}$ and aluminium in the kaolin (Al_{kao}) . Note though that the stoichiometric formula for kaolinite contains two Al atoms. Thus, all alkali in the fuel will have the theoretical possibility to be incorporated in the Al-silicate structure. By considering the concentration of alkali from the standard fuel analysis (given as mg/kg_{dry fuel}) together with the molar weights of the elements of K (39.1 g/mole) and Na (22.99 g/mole) as well as the kaolinite (258.2 g/mole), the additive level in weight-% can be calculated. For normal stemwood based wood fuels (0.3-0.4 weight-% ash), this theoretical (stoichiometric) additivation level will be around 0.15 weight-% kaolin (on dry basis).

However, this initial theoretical level calculated for the kaolin additivation, should be adjusted regarding different considerations, e.g. the actual fraction of kaolinite in the kaolin clay (potential presence of other minerals e.g. quartz and feldspars), and the potential presence of cations already present in the kaolinite/kaolin (e.g. K⁺, Na⁺, Ca²⁺, Mg²⁺). Due to the differences in ionic charge, it can be assumed that for each extra (already present) mole of K and Na, one mole of the kaolinite will be occupied, while for each mole of Ca and Mg, two moles of kaolinite will be occupied. In addition, potential reactions between the kaolinite and alkali earth metals (Ca and Mg) already present in the fuel ash, should be considered, especially for woody fuels rich in Ca. All these issues will reduce the "efficiency" of the added kaolin and thus result in a need for increased levels of additivation to achieve the aimed effects. Finally, also physical properties of the kaolin (grain size, moisture content, etc.) needs to be considered as well as more practical operational considerations related to e.g. losses during the supply of the additive, risk for entrainment of unreacted additive particles through the boiler, and too high temperatures on the grate (as mentioned above).

4.2.2 Successful examples with kaolin additivation

A good example for a successful implementation of kaolin was made in the project with short rotation poplar. This poplar was tested both as a chipped fuel and as pellets which were produced from the same raw material. Furthermore, two additivation approaches were tested with poplar, the co-pelletisation of kaolin, and the addition of kaolin after pelletisation (Poplar pellets + 1.5% kaolin "powdered"). For chipped poplar the addition of the kaolin was performed





separately via a supplemental screw conveyor which was added to the fuel feeding system. For the test runs a small-scale (30 kW) moving grate boiler was used. The duration of the test runs was 8 h of steady state full load operation for each fuel. 4 TPM (total particulate matter) measurements, each with a sampling duration of 30 min, were evenly distributed over the 8 h test runs. Gaseous emissions were measured continuously throughout the test runs and evaluated for the same timeframes as the TPM sampling.

Figure 3 shows the results regarding the CO emissions and Figure 4 shows the TPM emissions for all poplar fuels tested within the project. The CO emissions for pure poplar pellets $(1,389 \text{ mg/Nm}^3 \text{ related to dry flue gas and } 13 \text{ vol}\% \text{ O}_2)$ as well as the TPM emissions $(156 \text{ mg/Nm}^3 \text{ related to dry flue gas and } 13 \text{ vol}\% \text{ O}_2)$ were very high, which is typical for this fuel when used in small-scale boilers [15]. By co-pelletized additivation with 1.5 w-% kaolin the CO emissions could be reduced by 92 % and the TPM emissions by 71 % compared to pure poplar. When the pure poplar pellets where powdered with 1.5 w-% kaolin, the CO and TPM emission reductions were somewhat lower (-76 % and -56 %, respectively), but still the measure proved to be quite effective.

When non-pelletized and non-additivated poplar chips were applied the CO emissions were a little bit lower than for pellets (886 mg/Nm³), and the TSP emissions (179 mg/Nm³) were slightly higher. But with the seperately added kaolin (approx. 1.5 w-%) via a screw conveyor the CO emissions were again largely reduced by 95 % and the TSP emissions declined by 44 % for these wood chips.

The results of the combustion tests clearly show that a significant reduction of both CO and TPM emissions can be achieved by additivation with kaolin under practical conditions. Furthermore, it can be concluded that co-pelletizing kaolin and poplar is a more effective additivation approach than when kaolin is seperatly added to the fuel pellets. Several reasons for this observation can be discussed such as; 1) seggregation of the kaolin, 2) loss of the kaolin in the fuel feeding system, 3) kaolin entrainment into the flue gas system where it cannot contribute to ash-chemical processes but will rather add to particulate emissions, and 4) less homogeneous mixing for the kaolin with the biomass during separate additivation compared to co-pelletisation. Entrainment of the kaolin with the flue gas is also believed to be correlated with the particle size of the kaolin powder used, however, practical suggestions for a proper choice of a best suitable kaolin texture can yet not be made.







Figure 3: CO emissions for poplar fuels and the different kaolin additivation approaches as tested in the project

Explanations: STC = standard testing conditions (dry flue gas, 0 $^{\circ}$ C, 1013 hPa, based on 13 $^{\circ}$ O₂)



Figure 4: TPM emissions for poplar fuels and the different kaolin additivation approaches as tested in the project.

Explanations: STC = standard testing conditions (dry flue gas, 0 °C, 1013 hPa, based on 13 % O₂)





However the additivation with kaolin can also be associated with some disadvantages concerning pollutant emissions, mainly related to the potential for increased SO₂ and HCI emissions. As illustrated by the fuel compositions in Figure 3, this should preferably be relevant for agricultural fuels with high S and CI contents. The underlying mechanism explaining this effect by kaolin is related to the reduced amount of volatilized K (and Na) that subsequently can react with HCl and SO₂/SO₃ in the flue gases. Thus, higher HCl and SO₂ emissions can be expected, along with the reduced alkali salt containing fine particulate emissions. Within the test runs during the BIOFLEX! project, this effect was seen for sunflower husk, grass and wheat straw concerning SO₂ (Figure 5) and for grass and wheat straw for HCl (Figure 6). For SO₂, this implies that the threshold set by the European MCP (medium plant combustion) directive (i.e. 200 mg/m^3 based on $6\% O_2$) was clearly exceeded for during the tests with sunflower husk and grass pellets, but also during the tests with wheat straw. Most obvious was this case for grass fuel, where the high K/Si ratio (Figure 3) promotes an excess of released K available for aerosol reactions with SO₂ and HCl in the flue gases. However, when K is efficiently captured by kaolin, the emissions of both SO₂ and HCl increase drastically. Consequently, the use of additives for small-scale furnaces seems more promising for problematic agricultural wood fuels with low amounts of chlorine and sulphur, such as poplar fuels from short rotation coppice.

4.3 Guideline for kaolin additivation – fuel-, additive- and practical considerations

Based on new knowledge and experiences gained from the *BIOFLEX!* project, in combination with reported scientific literature and previous experiences from research, development and full-scale tests, the following recommendations regarding the use of fuel additives in general and of kaolin in particular can be defined. This guideline is presented as a step-wise procedure to follow, targeting different steps of the additivation application, and with the intention to support a successful implementation.

- 1. **Type of combustion system** where the additivation will be applied what problems are considered (e.g. slagging, deposit formation, fine particle emissions, total dust emissions) and what is expected to be achieved by the additiviation.
 - In small and medium-scale fixed-bed systems (grate boilers and small burners), the main targets for using kaolin as additive are to reduce slagging tendencies and fine particulate emissions. Also deposits formed by alkali salts will be reduced, but they are not often an issue in these applications.
 - Total dust emissions are most often reduced as an effect of less fine PM, but the potential entrainment of coarse mineral particles (kaolin powder) needs to be considered and preferably avoided. The risk for increased slag formation on the grate (only for rather pure wood fuels) should also be assessed from case to case, since in general this is not significant, but still needs to be considered.
- 2. **Type of fuel(s) used** presently and expected in a relevant future in principle three classes can be defined; i) pure wood fuels (stemwood based), ii) ash rich woody energy crops and forest residues, and iii) grass/straw based fuels.





- Separate recommendations are made for these three categories since the variations in ash content and compositions have major effects on the function and applicability of different additives, not least for the kaolin mineral additive.
- For "clean" woody fuels (e.g. Stemwwod based fuels with low Si contents) kaolin will mainly be applied for fine PM emission reduction. However, the risk for slag formation needs to be carefully assessed, and may be controlled by lowering the fuel bed temperature.
- For Si-rich straw and grass fuels, kaolin has positive effects on both fine PM emissions and slag formation. However, comparably high additive levels are needed to achieve significant effects, and the total system aspects, e.g. material flows, ash handling, legislation (emissions, ash, etc..), techno-economical aspects, etc. need to be carefully assessed.
- Additive to use in this guideline the focus is on the clay kaolin to be used as fuel additive, due to its advantageous properties compared to most other similar aluminium-silicate based minerals. Some quality aspects needs to be considered to enable an efficient application, related to both physical and chemical properties of the kaolin.
 - Different commercial qualities of kaolin exist, so both technical and economic aspects needs to be considered. Quality aspects to consider are e.g. the purity of the kaolin, the grain size, moisture content and the contents of contaminants.
 - High purity of the kaolin, i.e. a high fraction of the kaolinite mineral, low concentrations of K, Na, Ca and Mg as well as low concentrations of heavy metals is preferable. This promotes a more straight forward estimation of the additivation level to optimize the effects and avoid unwanted additional environmental considerations. It should be noted that kaolin as such is dominated by the mineral kaolinite, and will therefore in all cases give the discussed ash chemical effects, although potentially with varying efficieny and with some side-effects that need to be accounted for, depending on the specific kaolin properties.
 - A smaller and homogeneous grain is preferable due to the higher "reactivity" (efficiency) of the additive. However, the risk for entrainment of (small) unreacted mineral dust particles from the bed to the flue gas system should be considered. Optimization studies regarding this issue specifically for fixed-bed systems, have not been reported (not to the authors' knowledge), so both practical, technical and economic aspects should be considered from case to case.
- 4. Additivation level to apply Examples of additivation levels applied within *BIOFLEX*! are here given, as well as a simple calculation approach and some considerations and recommendations
 - In *BIOFLEX!* the kaolin levels applied were calculated first as the theoretical minimum level assuming that 100% of the kaolin is kaolinite, all kaolinite is available for reactions with fuel alkali and no other/practical limitations of the efficiency of the kaolin exist. The applied levels were then increased in the range of +12 to 50%, depending on different considerations (see following paragraphs).





(Eq. 1)

(Eq. 3)

Fuel	Ash content (wt-% db)	Kaolin level (theo. min) (wt-% db)	Kaolin level (applied) (wt-% db)
Poplar	2.2	1.0	1.5
Wheat straw	4.3	2.8	3.4
Grass	8.5	7.0	8.1, 10.5
Sunflower husk	2.9	2.5	2.8

To calculate the suitable level of kaolin for additivation, the first step is to re-calculate both the fuel and kaolin composition data, for the major ash forming elements, from mg/kg (db - dry basis) to mole/kg (db) by deviding the mass based element content with the respective mole weight (K: 39.1 g/mole, Na: 22.99 g/mole, Ca: 40.08 g/mole and Mg: 24.31 g/mole). The next step is to calculate the theoretical minimum amount (mole) additive Al₂Si₂O₅(OH)₄ needed per kg fuel to capture all alkali metals (K_{fuel} + Na_{fuel}), based on the assumptions mentioned above, according to equation 1:

Additive_{theo min} = (K_{fuel} + Na_{fuel})/2

- Further, the potential presence of elements such as K, Na, Ca and Mg in the additive (K_{add}, Na_{add}, ...) should be adjusted for, by considering the fraction of these elements in relation to the concentration of Al in the kaolin (Al_{add}), according to equation 2:

$$Additive_{adj(l)} = Additive_{theo min} / ((Al_{add} - K_{add} - Na_{add} - 2(Ca_{add} + Mg_{add})) / Al_{add})$$
(Eq. 2)

- To further also account and adjust for other potential uncertainties and potential limiting effects for the additive functionality, availability and efficiency a factor of e.g. 90% can be assumed, and implemented according to equation 3:

Additive_{adj(II)} = Additive_{adj(I)} / 0.9

- This efficiency factor may, of course, be adjusted based on case specific conditions and own experiences by the users of this tool. For example, if kaolin is used together with rather pure woody biomasses (Si-poor), Ca in the fuel may interact with the kaolinite, thus lowering the capturing efficiency of K and Na. In that case, somewhat further excess kaolin levels may be suitable. Also aspects such as high fuel bed temperatures and high gas velocities through the fuel bed, may lower the overall efficiency of the kaolin additivation.
- Finally, the molar amount of additive needed per kg fuel, can be re-calculated to mass amount per kg fuel, by considering the molar mass of kaolinite (258.2 g/mole), which also enables the calculation of the wt-% of kaolin applied for the specific additivation case.
- 5. Additivation approach; either co-pelletized or separately as powder mixed with the fuel. An additional option, although not studied within *BIOFLEX!*, is to supply the additive as a slurry to the fuel feeding system. Based on the results from the *BIOFLEX!* project and supported by full-scale tests performed within another Swedish project [14], co-pelletizing the additive with the biomass fuel is recommended from an additive efficiency point of view, and if pellets are used as base fuel. This approach may not be the most suitable in all cases, for different more or less obvious reasons.





- If the additive is supplied separately, a suitable solution for the introduction of the kaolin powder (e.g. separate screw feeder) needs to be applied, preferably docked to the fuel feeding system just before the fuel enters the boiler.
- In full-scale tests, performed in the above mentioned Swedish national project, this approach has proven to be suitable, although it has so far only been applied in short-term tests (some days). In a long-term operation perspective, several aspects related to e.g. varying load conditions, varying fuel quality, durability and maintenance etc, need to be carefully assessed and considered.
- 6. Implementation considerations For full-scale implementation of an additivation concept, as with kaolin, several technical, practical, and economical aspects need to be considered. Most of them have not been studied within the *BIOFLEX!* project, and even if rather extensive research has been performed on this topic, very few examples from full scale implementations have been performed, at least as reported in some kind of literature.
 - One important experience from the full-scale tests [14] was that the function and efficiency of the kaolin additivation in the used grate boiler clearly was dependent on load conditions, with more favourable conditions for an effective kaolin additivation during low load operation. This kind of practical operational effects in a full-scale application may of course vary considerably from case to case.
 - Beside the above mentioned aspects, some specific operation related aspects need certain attention:
 - precise process control of the boiler and the whole plant is needed to achieve stable load and combustion conditions
 - possibilities to separately control the primary and seconday air supply in order to adjust the conditions on the grate and to keep the fuel bed temperatures below or in the range of 1,000 °C by appropriate air staging are recommended
 - stable additivation ratios will be maintained, preferably by co-pelletizing the additive with the biomass (if pellets are used), or by a stable separtely controlled additive feeding system (e.g. screw feeder)

4.4 Summary and recommendations

Overall, the use of different fuel design concepts like fuel additives or fuel blending have great potentials to be used as efficient strategies to mitigate ash related operational problems and to reduce fine particulate emissions. Within the project *BIOFLEX!*, the concept of using the clay mineral kaolin as additive in small- and medium scale grate fired biomass systems has been studied, tested and further developed, resulting in the specific recommendations provided in these guidelines.

5 Boiler concepts for challenging biomass fuels

5.1 Fuel-flexible combustion plant operation – general aspects

State-of-the-art small and medium-scale combustion concepts significantly differ regarding several aspects. Typically this concerns the fuel feeding strategies, the grate concepts, the





furnace geometries, the furnace cooling concepts, the air distribution and combustion air supply control concept, the number of sensors applied for process control as well as the process control concepts. Therefore, in the following small and medium-scale combustion plants are discussed separately. The small scale thereby refers to plants with boiler capacities up to 500 kW_{th} and the medium scale to installation with thermal capacities between 500 kW_{th} and 10 MW_{th}.

Modern small-scale biomass boilers are typically designed for the application of high quality wood pellets (EN 17225-2, class A1) and wood chips with restricted moisture and ash contents. The boiler concepts are typically tailored to serial production. Consequently, within one model series, only minor adaptations can be realised to enhance fuel flexibility. Therefore, it is generally meaningful to design new fuel-flexible model series based on existing pellet and wood chip combustion technologies by applying the measures proposed in the following.

In the medium-scale capacity range however, the plant concepts are usually developed based on the constraints of their application at the respective client, thus they are tailored to specific applications. Therefore, a much broader fuel spectrum is typically utilised, mainly comprising wood pellets and wood chips of various qualities regarding moisture and ash content as well as bark. Consequently, application respectively client specific design measures to improve fuel quality can be implemented.

5.2 Design related aspects for small-scale combustion plants

5.2.1 Fuel feeding system

The energy density and particle size of the biomass fuel are the most relevant parameters regarding the design of the fuel feeding system. Therefore, for enhancing the fuel flexibility, the bulk density of the fuel and its particle size are determining parameters. Experience from the test runs performed within *BIOFLEX!* revealed that when utilising pelletised fuels, the common fuel feeding systems of modern pellet boilers can be applied without modifications. In case of chipped and chopped fuels however, the bulk density must be carefully taken into account. For chipped fuels from short rotation forestry (e.g. poplar) common fuel feeding systems as used for conventional wood chips are applicable. Chopped herbaceous fuels (e.g. straw, miscanthus) however, show much lower bulk and energy densities and larger particles, which are typically not suitable for this kind of feeding systems. Therefore, it is recommended to use them in pelletised form only.

5.2.2 Grate concept and de-ashing of the grate

Most challenging biomass fuels are characterised by significantly higher ash contents than wood pellets or wood chips (see Table 1). Therefore, the grate system and especially the deashing of the grate play a major role in combustion technology design.

Generally it is of relevance, that the fuel is evenly distributed over the grate in order to avoid uncovered areas. In this respect, a well-designed interface of the fuel feeding system with the first grate section (geometry of the opening from the fuel feeding system to the grate) is needed.





Due to the higher ash content an ash layer quickly forms on the grate which has to be continuously removed. Consequently, the application of moving grate systems with continuous de-ashing is recommended. Movements of the grate elements thereby can support the breaking of sintered ash agglomerates. Moreover, the grate area has to be adjusted to the higher ash contents of the fuels and to the longer residence time needed for a complete charcoal burnout.

These measures support to maintain an evenly distributed primary air supply and to avoid channelling in the fuel bed. Channelling means that zones with high primary air flows through the fuel bed are formed which lead to temperature peaks in the fuel bed and the formation of CO-rich streaks in the gases, which sometimes cannot be fully oxidised in the secondary combustion zone.

Moreover, it has to be considered that pelletised fuels with high ash contents partly keep their shape during combustion. That means that from the fuel pellets ash pellets are formed, which have a much higher volume than granular ashes (see Figure 5). This aspect has to be taken into account regarding the design of the de-ashing of the grate, the de-ashing screws and the ash bin. However, experience from test runs has shown that, if no significant ash sintering occurs, these ash pellets easily disintegrate during transport in a de-ashing screw.

Especially when utilising fuels with low ash melting temperatures, a certain formation of sintered and partly molten ash agglomerates must always be taken into account. Therefore, it is recommended to select a robust de-ashing screw designs, which is also capable to transport and break such ash agglomerates.



Figure 5: Ash pellets on the grate of a small-scale biomass boiler when firing wheat straw pellets

5.2.3 Application of advanced air staging concepts including flue gas recirculation

Ash melting on the grate is one of the most relevant problems when utilising agricultural biomass fuels. The application of advanced air staging in combination with flue gas recirculation has turned out to be an appropriate measure to keep the fuel bed temperatures low and to reduce respectively avoid slagging problems.

5.2.3.1 Furnace geometries

The furnace must have two geometrically well-defined combustion zones, namely a primary combustion chamber (which includes the fuel bed zone) and a secondary combustion chamber.

These zones should be geometrically separated in order to create a dedicated zone with reducing atmosphere in the primary combustion zone, which is also a relevant pre-requisite for a NO_x reduction by primary measures.





The volume of the primary combustion zone should be reasonably large since with increasing residence time NO_x emission reduction efficiency increases. Target values for the mean residence time (at flue gas temperatures between 800 and 1,000°C) are ideally ~1.0 s, however, a minimum residence time of ~0.5 s should be reached.

The volume of the secondary combustion chamber should be large enough to achieve a complete gas phase burnout at temperatures between 850 and 1,000°C. Typically one to two seconds are needed.

In order to optimise furnace and nozzle geometries, to achieve a good mixing between flue gas and air and to homogenise the temperatures in the different combustion zones, a CFD-based furnace design is recommended (see section 5.4).

5.2.3.2 Air staging concept

Advanced air staging means that the primary air ratio respectively the air ratio in the fuel bed should be low in order keep the fuel bed temperatures on a low level. Air ratios in the fuel bed of around 0.7 are therefore recommended.

By this measure also the gas velocities at fuel bed exit can be kept on a low level thus reducing the entrainment of fuel, charcoal and ash particles with the flue gases. This is also an important measure to reduce ash deposit formation in the secondary combustion chamber and the boiler as well as particulate emissions.

If flue gas is recirculated into the primary combustion zone (see section 5.2.3.3), the oxygen supplied with the recirculated flue gas has to be taken into account. Therefore, as a guiding value, air ratios above the fuel bed of about 0.8 are recommended.

At a given total excess air ratio (λ_{total}) of about 1.6 (typical value that can be achieved in smallscale boilers), the secondary air flow can be increased when low primary air ratios are applied. This bears the advantage that due to the higher momentum of the secondary air a better mixing of the combustion air and the flue gases in the secondary combustion zone takes place, thus improving gas phase burnout.

However, it has to be taken care that the secondary air injection is designed in a way that no reverse flows of secondary air into the primary combustion chamber occur. Such reverse flows can lead to increased temperatures on the fuel bed surface and also reduce the NO_x-reduction efficiency of the advanced air staging concept.

5.2.3.3 Flue gas recirculation

As a second measure to keep the combustion temperatures at a low level, the implementation of flue gas recirculation is recommended. In general, flue gas extracted from the flue gas flow downstream the boiler may be recirculated below and above the fuel bed. Flue gas recirculation below the fuel bed contributes on the one hand to fuel bed cooling but on the other side also to an increase of the gas flow through the fuel bed. In small-scale applications this typically leads to increased gas velocities at the fuel bed exit and thus to undesired entrainment of fuel, charcoal and ash particles with the flue gas.





Therefore, it is recommended to apply flue gas recirculation into the primary combustion zone above the fuel bed. By this measure the temperatures in the primary combustion zone should be kept at about 900°C. Thereby it has to be taken care, that the injection nozzles for flue gas recirculation are arranged in a way that no backflow of the recirculated flue gas towards the fuel bed occurs. Flue gas recirculation into the primary combustion zone bears several advantages:

- The fuel bed surface is cooled due to less radiation from above
- A better mixing of the gases released from the fuel bed can be achieved
- The formation of molten fly ash particles which cause deposit build-up in the combustion chamber can be avoided due to the lower temperatures
- The temperatures in the secondary combustion chamber can be reduced.

5.2.4 Avoidance of false air intake

An exact control of the combustion air flows is essential for the implementation of an advanced air staging concept. False air is thereby a disrupting factor since it represents an uncontrolled and not defined combustion air intake. As a guiding value, false air intake should be kept below 10% of the whole combustion air supplied. Besides not well sealed inspection openings of the furnace the fuel feeding system and the de-ashing system are the most relevant sources for false air in small-scale boilers.

It is expected to minimise false air intake through the fuel feeding system by e.g. the application of air tight rotary valves in the fuel supply line. Moreover, the de-ashing system should be air tight and the ash containers should be well sealed. Operation at low furnace underpressure also helps to reduce false air intake.

5.2.5 Furnace cooling

In general, the primary combustion chamber should be well insulated. In common concepts of small-scale biomass boilers the secondary combustion chamber is typically cooled by water jackets (radiative boiler section). It has to be considered that flue gas recirculation reduces the temperatures in the secondary combustion zone. To achieve an almost complete gas phase burnout (low CO and OGC emissions as well as practically zero emissions of soot and organic aerosols) also during partial load operation the residence time at high temperatures (above $900 - 1000^{\circ}$ C) must be long enough. Therefore, it is recommended to also insulate the first part of the secondary combustion chamber.

5.2.6 Boiler design and boiler cleaning

Since increased fuel flexibility is always connected to robustness towards different ash contents and thus fly ash contents of the flue gases, the boiler concept must be capable to operate at such conditions. It is recommended to implement automated boiler tube cleaning devices which are operated more frequently than in conventional pellet and wood chip boilers. Moreover, the boiler design should be based on the consideration of higher fouling rates than during wood chip and pellet combustion.





If fuels with elevated S and CI contents are utilised, low temperature corrosion may cause problems in the boiler due to acid dew point corrosion and the formation of corrosive hygroscopic salt deposits. According to results of low-temperature corrosion probe measurements, performed during straw pellet combustion within the *BIOFLEX!* project, it is recommended to operate the boiler at return temperatures of at least 60 to 65°C. Thus an appropriate control of the boiler return temperature is needed.

5.2.7 Secondary measures regarding emission control

Due to the elevated ash and especially K contents of agricultural biomass fuels elevated particulate emissions in comparison with wood combustion occur. Therefore, usually the application of a particle filter (electrostatic precipitator - ESP) is needed. Regarding the design of such ESPs it has to be considered that the particle contents in the raw gas are higher compared to wood combustion and that fine particulate matter (particles smaller than 1 μ m) clearly dominate the total dust emissions. Therefore, higher precipitation efficiencies especially for fine particulate matter are needed to achieve the same level of particulate emissions as for wood combustion.

Moreover, when utilising fuels with elevated S and Cl contents, filter surfaces have to be kept at appropriately high temperatures to avoid problems with low temperature corrosion (see also section 5.2.6).

5.2.8 Process control concept

To implement the measures mentioned above, the application of an appropriate process control concept is essential. This also concerns the process control hardware. In this respect it is important that the primary and secondary combustion air flows as well as the flue gas recirculation can be controlled exactly and independently. To gain more flexibility regarding the air staging settings it is recommended to implement process control strategies which allow for a flexible adjustment of the primary and secondary air flows and not systems with a fixed primary to secondary air flow ratio.

A second important aspect is the implementation of combustion chamber temperature control loops. To avoid the formation of sintered or molten ash deposits, the furnace temperatures have to be kept at an appropriately low level which depends on the ash melting characteristics of the fuels applied. Therefore, automated control loops for the flue gas recirculation in dependence of the combustion chamber temperature should be implemented.

To avoid problems with low-temperature corrosion, an appropriate control of the return water temperature is also recommended.

Moreover, the control of the ESP (start-up, shut down, cleaning cycles) has to be integrated into the process control system of the boiler.

5.3 Design related aspects for medium-scale combustion plants

5.3.1 Fuel feeding system

In medium-scale combustion plants screw feeding systems as well as hydraulic piston stokers are usually applied. Both systems are also applicable for fuel-flexible combustion systems.



However, it is important to select and design the fuel feeding system with respect to the bulk flow properties and the energy densities of the fuel assortments under consideration.

An important aspect thereby is that the fuel is evenly distributed over the whole grate area at the entrance. Moreover, the fuel should not be compacted too much during fuel feeding in order to facilitate an even gas flow through the fuel bed from the beginning. In this respect, screw feeding systems are preferred to piston feeders.

5.3.2 Grate concept and de-ashing of the grate

Due to the high variation range of the ash contents only moving grate based systems should be applied (no underfeed stokers). Inclined moving grates are preferred since they lead to a better mixing of the fuel bed and due to the movements of the gate elements, sintered or partly molten ash agglomerates can be broken. Moreover, the grate area has to be adjusted to the moisture content and the ash content of the fuels in order to facilitate an almost complete charcoal burnout.

It is recommended to design grates with more than two independently movable zones with separate primary air supplies. By this measure flexibility regarding the utilisation of fuels with different moisture contents, ash contents and bulk densities can be achieved. Thereby it has to be taken care that the primary air supply over the individual grate zones should be as homogeneous as possible which can be supported by small grate bars with a high number of air nozzles in the grate bars. Moreover, the air supply zones below the grate should be well sealed against each other in order to facilitate an exact adjustment of the air supply in the different grate zones.

Furthermore, the application of water cooled grates can reduce problems with slag formation on the grate. It is recommended to at least foresee a water cooling of the grate frame.

It is important that the grate is well sealed against the walls of the primary combustion zone since high combustion air flows along the walls can lead to local temperature peaks and consequently to ash sintering and ash melting effects. Moreover, such flows induce strains along the furnace walls which have a negative impact on gas phase burnout in the secondary combustion zone.

During the combustion of ash rich fuels larger partly sintered ash agglomerates may form. Although they can be disintegrated during de-ashing with screws, they may block the ash discharge opening at the end of the grate. Therefore, it is important that this opening is designed wide enough to also discharge larger ash agglomerates without blockages.

The de-ashing screws should be robust to avoid problems in case of the occurrence of slag pieces and the de-ashing system as well as the de-ashing interval must be adjusted to the range of ash contents expected for a plant.

5.3.3 Application of advanced air staging concepts including flue gas recirculation

Modern medium-scale combustion plants are typically based on air staging concepts and flue gas recirculation for fuel bed and combustion chamber temperature control. Existing concepts however have to be improved towards advanced air staging concepts if a higher fuel flexibility shall be achieved.





5.3.3.1 Furnace geometries

Typically, the furnaces consist of two geometrically well-defined combustion zones, the primary combustion chamber (which includes the fuel bed zone) and the secondary combustion chamber. It is important that these zones are geometrically well separated. In the zone above the fuel bed a reducing atmosphere should prevail in order to achieve a NO_x emission reduction by primary measures. The volume of this zone should be reasonably large since with increasing residence time NO_x emission reduction efficiency increases. Target values for the mean residence time (at flue gas temperatures between 800 and 1,000°C) are ideally ~1.0 s, however, a minimum residence time of ~0.5 s should be reached. Low-NO_x operation is especially of relevance for N-rich biomass fuels in order to avoid or minimise the efforts for secondary measures for NO_x emission reduction (see section 5.2.7).

It is also of relevance for the NO_x emission reduction efficiency that no backflows of secondary air into the primary combustion zone (respectively the reduction zone) occur.

The volume of the secondary combustion zone should be large enough to achieve a complete gas phase burnout. Moreover, it is recommended to foresee dedicated zones with low flue gas velocities or sharp direction changes of the flue gas flow in order to precipitate coarse fly ash particles from the flue gas by gravitational and/or centrifugal forces. These zones should either be automatically de-ashed or easily accessible for manual de-ashing.

Horizontal ducts should be avoided due to the risk of ash agglomerations and therefore vertically arranged combustion chambers are preferred.

In order to optimise furnace geometries as well as the geometries and positioning of nozzles for secondary air injection and flue gas recirculation, a CFD-based furnace design is recommended (see section 5.4).

5.3.3.2 Air staging concept

In contrast to conventional air staging advanced air staging means that the primary air ratio respectively the air ratio in the fuel bed should be decreased to values of about 0.5 or even lower in order keep the fuel bed temperatures on a low level. If flue gas recirculation below the grate is applied (see section 5.3.3.3), the oxygen supplied with the recirculated flue gas has to be considered when defining the primary air ratios. Moreover, regarding the air ratio in the primary combustion zone, also flue gas recirculated above the fuel bed has to be taken into account. As a guiding value, the air ratio in the primary combustion zone with flue gas recirculation above the grate should be in the range of 0.8.

By this measure also the gas velocities at fuel bed exit can be kept on a low level thus reducing the entrainment of fuel, charcoal and ash particles with the flue gases. This is also an important measure to reduce ash deposit formation in the secondary combustion chamber and the boiler as well as particulate emissions.

At a given total excess air ratio (λ_{total} – typically values between 1.4 and 1.6 can be reached), the secondary air flow can be increased when low primary air ratios are applied. This bears the advantage that due to the higher momentum of the secondary air a better mixing of the combustion air and the flue gases in the secondary combustion zone takes place, thus improving gas phase burnout.





As mentioned in section 5.2.2, the implementation of grate concepts with more than two zones with separately controllable primary air supply is recommended. In such systems, the primary air staging along the grate is also of relevance for the implementation of an advanced air staging concept. The air flows supplied to the zones where drying and biomass decomposition take place (typically the first and parts of the second grate zone) should generally be higher than the air flows supplied to the charcoal burnout zone. However, the air staging along the grate has always to be adjusted to the moisture content and ash content of the fuel as well as to the charcoal burnout time needed. To implement an efficient primary air staging along the grate it is important that the different air supply zones are well sealed against each other to prevent air flows from a zone with high air supply rates (and consequently higher local pressures) to zones with lower air supply rates (and lower local pressures).

5.3.3.3 Flue gas recirculation

As a second measure to keep the combustion temperatures on a low level the implementation of flue gas recirculation is recommended. In general, flue gas extracted from the flue gas flow downstream the particle filter should be recirculated below and above the fuel bed.

Flue recirculation below the fuel bed is used as a measure to cool the fuel bed and to avoid slag formation. It is recommended to restrict flue gas recirculation below the grate to the grate zones where drying and devolatilisation take place and not to inject recirculated flue gas into the charcoal combustion zone of the grate. The recirculated flue gas may be mixed with combustion air prior to injection below the grate or may be supplied separately.

Moreover, the injection of recirculated flue gas into the primary combustion zone above the fuel bed is recommended. By this measure the temperatures in the primary and the secondary combustion zone can be controlled. Moreover, flue gas recirculation above the grate improves the mixing of the gases in the reduction zone and thus supports NO_x -reduction reactions. Regarding the design and arrangement of the flue gas recirculation nozzles it has to be taken care that no backflows of recirculated flue gas towards the fuel bed surface, which may cause particle entrainment, occur.

Especially when utilising ash rich fuels an appropriate control of the combustion temperatures by flue gas recirculation is essential in order to avoid the formation of agglomerations of molten ash particles on the grate and sticky fly ash deposits on the furnace walls.

5.3.4 Avoidance of false air intake

An exact control of the combustion air flows is essential for the implementation of an advanced air staging concept. False air is thereby a disrupting factor since it represents an uncontrolled and not defined combustion air intake. Besides not well sealed inspection openings of the furnace, the fuel feeding system and the de-ashing system are relevant sources for false air. Moreover, purging air streams for keeping observation windows and optical ports of fuel bed level control systems clean may also provide significant sources for false air.

These false air sources should be minimised as good as possible. As a target value the share of false air on the total combustion air supplied should be below 15%. This may also be supported by an operation at the lowest possible underpressure in the furnace, since high underpressure accelerates false air flows. However, it is recommended to check the false air





intake during the initial start-up phase by air supply measurements and mass balances over the furnace. False air flows detected should be considered, according to their allocation, when calculating the primary air ratios and combustion air ratios in the fuel bed and the primary combustion zone. The set values for the air supply control should be adjusted accordingly to include also the influence of false air streams.

5.3.5 Boiler design and boiler cleaning

State-of-the-art medium-scale combustion plants are usually equipped with automated boiler cleaning systems based on pressurised air. Such cleaning systems should be foreseen in any case since the increased ash contents and especially increased contents of fine particulate matter forming elements (in particular of K) lead to increased fouling. The systems should be operated more frequently than in wood combustion in order to keep the temperatures at boiler outlet on an acceptable level. Increased fouling however, should already be considered during boiler design.

As long as hot water boilers are applied, no risks regarding high temperature corrosion have to be expected. These risks increase with increasing wall temperatures of the heat exchangers and therefore, corrosion risks have to be regarded for thermal oil boilers and especially for superheater sections of steam boilers. In any case an efficient boiler cleaning system reduces the residence time of corrosive compounds on the boiler tube surfaces and thereby helps to reduce corrosion related risks.

With increasing S and CI content of the fuel also the risks for low temperature corrosion increases. According to latest data, low temperature corrosion is most probably induced by depositions of corrosive hygroscopic salts. In [2] it is recommended to keep the gas-side boiler surface temperatures

- for dry fuels and flue gas water contents of up to 15 vol.% above 70°C
- for fuels with high moisture contents and consequently flue gas water contents of more than 20 vol.%, above 90°C.

These proposed minimum surface temperatures already include a safety margin which is needed to consider a certain range of fluctuations of plant operation

5.3.6 Secondary measures regarding emission control

Due to the high variation ranges of possible ash contents and especially K-contents, secondary dust emission control measures are needed. If no other measures for emission control must be implemented (e.g. dry sorption for HCl and/or SO₂ removal), the application of electrostatic precipitators is recommended. In combination with dry sorption systems for HCl/SO₂ removal, baghouse filters shall be applied.

For fuels with high N contents the implementation of advanced air staging concepts may not be sufficient to keep the NO_x emission limit values. In such cases a SNCR (selective non catalytic reduction) system must be implemented. Thereby, urea or ammonia is injected into the secondary combustion zone at a position where an almost complete burnout is already achieved and at temperature levels of about 850 to 1,000°C. Since a certain residence time at these temperatures is needed for the NO_x reduction reactions, the volume of the secondary





combustion zone has to be adjusted to the demands of the SNCR system. Appropriate guiding values, which have to be considered during furnace design, are provided by the suppliers of SNCR units.

5.3.7 Process control concept

It is important to mention that the process control strategy supports the implementation of the measures explained above. Therefore, the control system must assure an exact control of air ratios and combustion chamber temperatures in order to achieve continuous low-emission operation of the combustion plant.

5.4 CFD based boiler design as an efficient measure to achieve a higher fuel flexibility

Regarding some of the measures mentioned in section 5.2 and 5.3 already a certain awareness at furnace and boiler manufacturers exists. However, their correct implementation into real applications represents the major problem and challenge. In order to improve the implementation of primary measures in furnaces and boilers, process simulation based on computational fluid dynamics (CFD) has become a design instrument which allows for a quicker and more efficient development process than traditionally applied experimental development work.

With CFD it is possible to simulate the combustion process in detail, and thereby to analyse velocity and temperature distributions in the furnace as well as the combustion reactions. CFD can therefore be applied in order to optimise furnace geometries as well as air supply and flue gas reciculation strategies (e.g. injection nozzle dimensions, arrangements and location) in a way that the primary measures discussed above can be implemented in an optimised way. The variation of different parameters regarding combustion chamber insulation respectively cooling measures (selection of specific insulation materials and insulation strategies, flue gas recirculation, cooling by water jackets) can lead to optimised solutions to reach the targeted combustion chamber temperatures and an almost complete gas phase burnout during full and partial load operation. Moreover, the results of the calculations are visualised and therefore provide the basis for an improved understanding of the processes going on.

CFD simulations cannot substitute classic experimental R&D, but they can significantly increase the probability of the success of the development work and speed up the development process. By the simulation of different load cases and fuels, CFD simulations additionally provide relevant basic information for developing an optimised process control concept tailored to the demands of the respective technology.





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