

THE PRESENT STATE AND FUTURE DEVELOPMENT OF INDUSTRIAL BIOMASS COMBUSTION FOR HEAT AND POWER GENERATION

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ABSTRACT

The energetic utilisation of solid biomass is expected to play a major role in future concepts for the reduction of greenhouse gas emissions. Within the field of energetic biomass utilisation combustion is the most advanced and market-proven application. A broad spectrum of biomass combustion technologies for heat and electricity production and for different types of biomass fuels (woody and herbaceous biomass fuels, biodegradable wastes and residues) covering a wide range of plant capacities (from a few kW to several hundred MW) is currently available. Concerning plant design chemical and physical properties of biomass fuels are of great importance. In this paper, these properties are discussed with a special focus on relevant guiding parameters and on ash related problems, like aerosol formation, slagging, deposit formation and corrosion. Furthermore, the present state-of-science concerning the design of biomass combustion system by means of CFD simulations, gaseous emissions under special consideration of NO_x and new control concepts for biomass combustion plants are presented. Future developments mainly focus on the utilisation of new biomass fuels, the further development of combustion technology towards “zero emissions” systems, on efficiency improvements and increased availability (e.g. reduction of deposit formation and fouling).

INTRODUCTION

In recent years the thermal utilisation of solid biomass for heat and electricity production has gained great importance. Within the European Union in particular, biomass is seen as the most relevant renewable energy source besides hydropower and is thus expected to substantially contribute to the CO_2 emission reduction targets defined in the Kyoto protocol. There is a broad international consensus that the utilisation of renewable energy sources should be further enforced in order to reduce greenhouse gas emissions. The increase of fossil fuel prices due to increasing energy demand and limited resources is a major driving force towards renewable energy.

In the EU, several political measures have been initiated with the aim of supporting the utilisation of renewable energies including the Res-e Directive (2001), the EU Biomass action plan (2005), Energy & Climate Change Package (March 2007), and the Renewable Energy Directive (June 2009). Within the scope of the Energy & climate change package the following targets have been defined:

- 20% renewables by 2020
- 20% reduction of greenhouse gas emissions by 2020
- 20% increase of energy efficiency
- 10% increase in biofuels by 2020

According to the renewable energy directive the target of 20% renewables by 2020 is now binding. Furthermore, targets for the EU member states will be defined which will be binding as well.

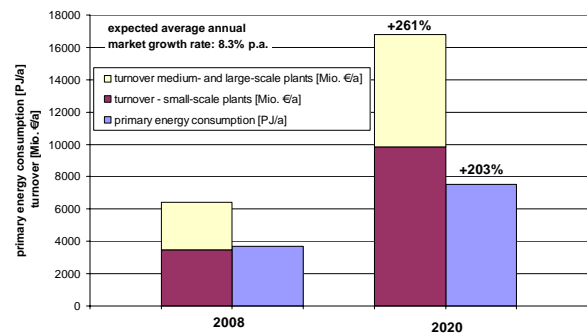


Figure 1: Estimated primary energy consumption and total turnover of biomass combustion plants in the EU for 2008 and outlook 2020
Explanations: small-, medium-, and large-scale plants considered; small-scale plants: nominal boiler capacity < 100 kW_{th}; calculations based on present market and achievement of EU 2020 targets [1,2,3,4,5]

Figure 1 shows the estimated primary energy consumption and total turnover of biomass combustion plants in the EU for 2008 as well as the outlook for 2020. The calculations are based on the present market [1,2,3,4] and the assumption that the EU 2020 targets will be achieved [5]. The results show that an average market growth rate of approx. 8.3% p.a. is expected, the market volume should grow up to 260% and the primary energy consumption from biomass should be more than doubled until 2020.

BIOMASS COMBUSTION TECHNOLOGIES

As already mentioned the energetic utilisation of solid

biomass is expected to play a major role in future concepts for the reduction of greenhouse gas emissions from heat and electricity production. In general, three different technologies for thermal biomass conversion can be applied, namely pyrolysis, gasification and combustion. Combustion is the most advanced and market-proven application, while pyrolysis and gasification are still in the development or demonstration stages. Consequently, the energetic use of solid biomass is primarily based on biomass combustion at present and will be the dominant conversion technology in future.

A broad spectrum of biomass combustion technologies for different types of biomass fuels (woody biomass fuels, herbaceous biomass fuels, biodegradable wastes and residues) covering a wide range of plant capacities is currently available. In principle, the following combustion technologies can be distinguished (see Figure 2) [6]:

- fixed-bed combustion,
- fluidised bed combustion,
- pulverised fuel combustion.

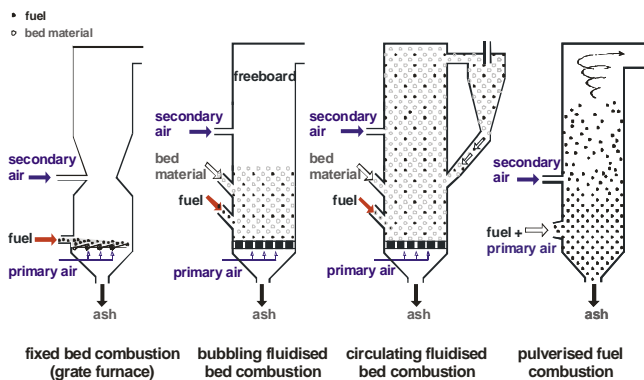


Figure 2: Overview of different biomass combustion technologies

Table 1: Overview of advantages, disadvantages and fields of application of different biomass combustion technologies

Advantages	Disadvantages
Fixed bed combustion - capacity range: 100 kW – 50 MW	
large flexibility concerning moisture content (10 – 60 wt% w.b.) and particle size (5 - >100 mm)	mixing of wood fuels and herbaceous fuels limited
mixing of different wood fuels possible	high excess oxygen (5 - 8 Vol%)
low investment costs for plants < 20 MW _{th}	decreases efficiency
low operating costs	combustion conditions not as homogeneous as in fluidised bed furnaces
less sensitive to slagging than fluidised bed furnaces	
Fluidized bed combustion - capacity range: 20 MW – several 100 MW	
high flexibility concerning moisture content (10 – 55 wt% w.b.) and kind of biomass fuels used	high investment costs, interesting only for plants > 20 MW _{th}
no moving parts in the hot combustion chamber	high operating costs
high specific heat transfer capacity due to high turbulence	low flexibility with regard to particle size (< 80 mm for BFB, 40 mm for CFB)
low excess oxygen (1 - 4 vol%) raises efficiency and decreases flue gas flow	high dust load in the flue gas
	partial-load operation requires special technology
	high sensitivity concerning ash slagging
Pulverised fuel combustion - capacity range: 500 kW – several 100 MW (co-firing)	
Medium excess oxygen (4 - 6 Vol%) increases efficiency	water content usually < 20 wt% w.b.
very good load control and fast alternation of load possible	particle size of biofuel is limited (< 10-20 mm)
	high wear out of the insulation brickwork if cyclone or vortex burners are used
	an extra start-up burner is necessary

In Table 1 an overview of advantages, disadvantages, fields of application and capacity ranges of different biomass combustion technologies is given.

Fixed-bed combustion systems include grate furnaces and underfeed stokers. Primary air passes through a fixed bed, in which drying, gasification, and charcoal combustion takes place. The combustible gases produced are burnt after secondary air addition has taken place, usually in a

combustion zone separated from the fuel bed. Fixed-bed combustion systems have a large flexibility concerning moisture content (10 – 60 wt% w.b.) and particle size (5 mm - >10 cm). Furthermore, the mixing of wood fuels is possible but limited for herbaceous fuels. The nominal boiler capacities range between 10 kW to 50 MW (see also Table 1).

Within a fluidised bed furnace, biomass fuel is burnt in suspension of gas and solid-bed material into which primary combustion air enters from below. Depending on the fluidisation velocity, bubbling fluidised bed and circulating fluidised bed combustion can be distinguished. In BFB furnaces, the bed material is located in the bottom part of the furnace with a fluidisation velocity between 1.0 and 2.5 m/s. By increasing the fluidising velocity to 5 to 10 m/s and using smaller biomass fuel and sand particles a CFB system is achieved. The sand particles are carried with the flue gas, separated in a hot cyclone or a U-beam separator, and fed back into the combustion chamber. Fluidised bed furnaces offer a large flexibility concerning moisture content (10 – 55 wt% w.b.) and fuel mixing but a low flexibility concerning particle size (< 80 mm for BFB and <40 mm for CFB systems). Due to the homogeneous combustion conditions given in fluidised bed systems, low excess air ratios are possible which raise the efficiency and thus compensate the higher investment costs with increasing capacity. The boiler capacity range covers 20 MW to several hundred MW (see Table 1).

Pulverised fuel combustion is suitable for fuels with small particle size. A mixture of fuel and primary combustion air is injected into the combustion chamber. Combustion takes place while the fuel is in suspension, and gas burnout is achieved after secondary air addition. Examples are dust injection burners, muffle furnaces and cyclone burners. The moisture content of the fuel is usually below 20 wt% w.b. and the particle size is limited up to 20 mm (see Table 1). Stand-alone applications as well as a combination with grate and fluidised bed combustion are possible (fuel staging). Moreover, this technology is the most common application for biomass co-firing. The boiler capacity of pulverised fuel combustion systems ranges from 500 kW to several hundred MW (for co-firing systems).

Concerning plant size, the different applications of biomass combustion can be divided into the following main fields:

- Small-scale biomass combustion systems: (capacity range: <100 kW_{th})
- Medium-scale combustion systems (capacity: range: 100 kW_{th} to 20 MW_{th})
- Large-scale combustion systems (capacity: range: >20 MW_{th})
- Co-firing of biomass in coal fired power stations (capacity range: some 100 MW_{th})

Small-scale biomass combustion units are mainly applied for residential heating systems. Here, different types of pellet burners, wood stoves and fire-place inserts as well as log wood, wood chips and pellets boilers are commonly used. These systems are only suitable for high quality wood fuels.

The **medium capacity range** covers biomass district and process heating and biomass combined heat and power (CHP) plants. Underfeed stokers, grate-fired furnaces and pulverised fuel burners are the main technologies applied in this capacity range. In Figure 3 examples for underfeed stokers and grate-fired furnaces are shown. Heat transfer is most commonly based on hot water boilers, but also steam boilers and thermal

oil boilers. These systems usually burn woody biomass fuels such as wood chips, sawdust, bark, forest residues and waste wood but also straw and other agricultural residues (e.g. sunflower husks). In addition to heat production for process and district heat supply, combined heat and power (CHP) systems are of increasing importance. A number of CHP technologies such as Stirling engines, the ORC process, steam engines and steam turbines can be combined with such plants.

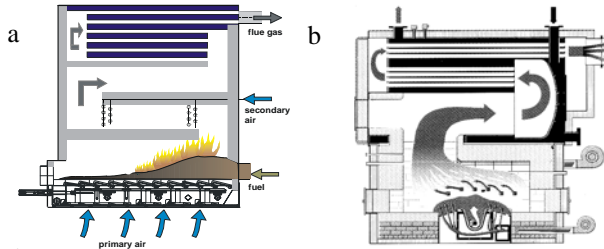


Figure 3: Medium-scale biomass combustion systems

Explanations: a) grate-fired furnace (source: MAWERA Holzfeuerungsanlagen GmbH); b) underfeed stoker (source: MAWERA Holzfeuerungsanlagen GmbH)

The **large-scale range** (>20 MW_{th}) mainly comprises CHP plants and power plants with thermal capacities up to some 100 MW based on grate-fired and fluidised bed combustion systems (see Figure 4). These are usually fired with woody biomass fuels (wood chips, sawdust, bark, forest residues and waste wood) and straw but also with residues and wastes from the agricultural industry such as fruit stones, kernels, husks and shells. Usually steam boilers combined with steam turbines are applied.

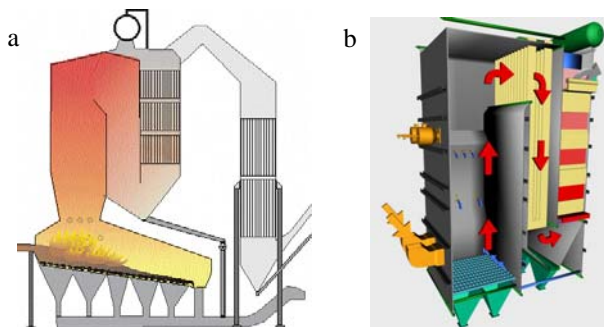


Figure 4: Large-scale biomass combustion systems

Explanations: a) grate-fired furnace (source: Josef Bertsch GmbH & Co); b) fluidised bed combustion (source: AE&E Austria GmbH & Co KG)

Co-firing of biomass fuels in large-scale coal fired power stations also represents an interesting option for biomass utilisation. Due to the large plant sizes co-firing offers great potential for CO₂ reduction in the short term if applied in existing power plants. The biomass co-firing options can be categorised as follows [6]:

- Biomass co-firing in existing pulverised coal combustion (PCC) systems
 - Co-firing of biomass on a separate grate directly under the coal boiler
 - Co-firing of finely milled biomass mingled with coal
 - Co-firing of finely milled biomass by separate injection
- Biomass co-firing in fluidised bed combustion (CFB and BFB) systems
- Biomass co-firing by using separate combustion units and junction of steam

- Biomass gasification and utilisation of the product gas as fuel in a coal combustion system

Dust injection burners or fluidised bed systems are mainly used. Figure 5 shows an example of a co-firing plant utilising milled straw in dust injection burners. The biomass input in co-firing units is usually restricted to about 10-20% (by mass) of the whole fuel input if existing coal-fired power stations are used.

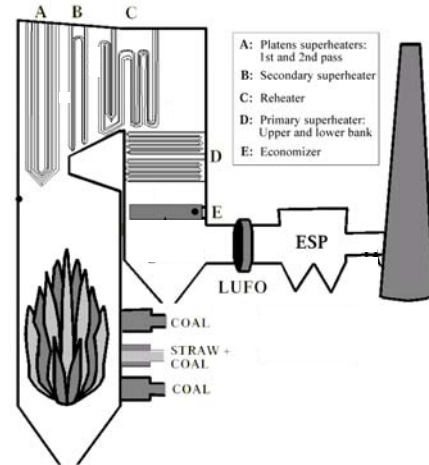


Figure 5: Co-firing of straw in a pulverised fuel boiler

Explanations: source: [7]

RELEVANT CHARACTERISTICS OF BIOMASS FUELS

The chemical composition of biomass fuels can vary concerning both, the concentrations of the main elements (C, H, O, N) as well as the ash content respectively the concentrations of ash forming elements. The ash content can be seen as a guiding parameter indicating increased ash related problems with raising ash content. However, more detailed information about the single ash forming elements is needed in order to evaluate a biomass fuel with respect to different ash related problems that can occur. Thereby also interactions between these elements have to be considered. In the following some specific characteristic parameters of biomass fuels, which can be taken as a basis for the evaluation of a fuel are summarised. It may also in many cases be helpful to calculate the fuel ash composition from the biomass fuel composition. The fuel ash represents the composition of the total ash formed during combustion. Its composition is calculated by dividing the concentrations of the single ash forming elements by the ash content of the fuel.

Table 2 shows important physical properties of solid biomass fuels and their effects on the combustion process and the plant design. The moisture content of the fuel provides information concerning the general applicability of a certain fuel in a combustion process and its storability.

The ash content has to be considered concerning the de-ashing 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 dust emissions. Therefore, it is an important parameter to be considered during plant design.

The ash melting behaviour of ash mixtures is characterised by the contents and by the melting temperatures of the single ash forming elements respectively their compounds. Si, Ca and Mg increase the ash melting temperature, while K, Na, and P as well as Cl decrease the

ash melting temperature. The ash melting behaviour affects the combustion technology and the process control system and is an important factor concerning deposit formation and operational safety.

The bulk density of the fuel has also to be considered concerning fuel transport, storage, and feeding systems.

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 (special quality parameter for pellets). In medium and large-scale plants the amount of fines is an important factor regarding particle entrainment (can cause strain formation and incomplete burnout).

Table 2: Combustion relevant characteristics of solid biomass fuels – physical properties

Properties	Effects
Moisture content	Storability, dry matter losses, NCV, self-ignition, plant design
NCV, GCV	Fuel utilisation, plant design
Volatiles	Thermal decomposition behaviour
Ash content	Dust emissions, ash manipulation, ash utilisation / disposal, combustion technology
Ash melting behaviour	Operational safety, combustion technology, process control system, hard deposit formation
Fungi	Health risks
Bulk density	Fuel logistics (storage, transport, handling)
Particle density	Thermal conductance, thermal decomposition
Physical dimension, form, size distribution	Hoisting and conveying, combustion technology, bridging, operational safety, drying, formation of dust
Amount of fines	Fuel feeding, particle entrainment
Abrasion resistance (wood pressings)	Quality changes, segregation, fine parts

In Table 3 combustion relevant chemical properties of solid biomass fuels are listed. For a complete characterisation of a biomass fuel contents of C, H, O and N as well as the gross calorific value (GCV) should be determined since they provide basic information concerning the general applicability of a certain fuel in a combustion process and regarding the energy content of a fuel. The N content is of special relevance concerning NO_x emissions.

Table 3: Combustion relevant characteristics of solid biomass fuels – chemical properties

Properties	Effects
Carbon (C)	GCV
Hydrogen (H)	GCV, NCV
Oxygen (O)	GCV
Chlorine (Cl)	HCl-, PCDD/F emissions, corrosion
Nitrogen (N)	NO _x -, N ₂ O emissions
Sulphur (S)	SO _x emissions, corrosion
Fluor (F)	HF emissions, corrosion
Potassium (K)	Corrosion (heat exchangers, superheaters), lowering ash melting temperature, formation of aerosols, ash utilisation (plant nutrient)
Sodium (Na)	Corrosion (heat exchangers, superheaters), lowering ash melting temperature, formation of aerosols
Magnesium (Mg)	Increase of ash melting temperature, ash utilisation (plant nutrient)
Calcium (Ca)	Increase of ash melting temperature, ash utilisation (plant nutrient)
Phosphor (P)	Ash utilisation (plant nutrient), ash melting, aerosol formation
Heavy metals	Emissions, ash utilisation, formation of aerosols

Moreover, ash forming elements have to be divided into non-volatile elements such as Si, Ca, Mg, Al and Fe, semi-volatile elements such as P and Mn and rather volatile elements such as K and Na. During combustion semi-volatile and especially volatile elements are partly released from the fuel to the flue gas and react with other elements such as S, Cl or CO₂ in the flue gas. Major ash forming elements originate either from the biomass (plant) itself or from impurities such as soil, stones and residues from the pre-processing of the

fuels. Elements such as P, K and Na for example are part of the cell matrix of plants and elements such as Ca and Si are embedded in the plant fibres. In wood fuels usually Ca is the dominating major ash forming element while in herbaceous biomass fuels significantly higher Si-contents prevail.

Subsequently, the resulting sulphate, chloride and also carbonate compounds may form fine particles by nucleation (formation of aerosols) or condense on already formed aerosols and coarse fly ash particles as well as on heat exchanger surfaces (ash deposit formation). In most fuels mainly K and Na are involved in these processes. In P rich fuels also a part of the organically bound P is released to the flue gas and is involved in aerosol and deposit formation mainly via the formation of KPO₃, P₂O₅ and P₄O₁₀ [8].

Minor ash forming elements (Zn, Pb, Cd, Cu, Cr, Co, Ni, Mo, As, Sb, Hg, Tl) are mainly of interest concerning problems with too high gaseous and particle bound heavy metal emissions as well as regarding the ash utilisation. Moreover, the presence of heavy metal chlorides in ash deposits can significantly reduce the melting temperatures of the deposits thus leading to increased deposit formation and corrosion rates.

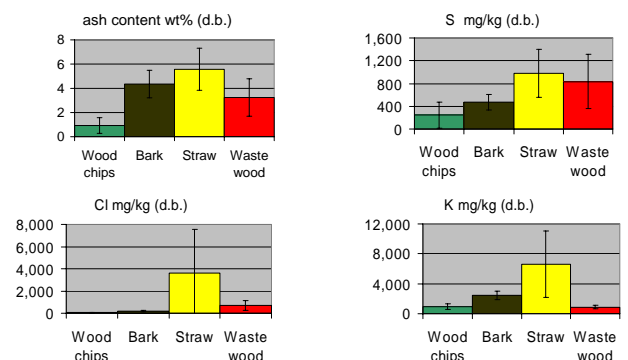


Figure 6: Chemical compositions of different solid biomass fuels - ash, S, Cl, K

S and Cl are relevant elements concerning gaseous emissions (SO_x, HCl), 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 K₂SO₄ and KCl. High Cl-contents of the fuel therefore also increase corrosion related problems especially due to ash deposits with high Cl-contents. Moreover, Cl reduces the ash melting temperature of deposits. Due to these deposit formation and corrosion related issues an impact of the S- and Cl-contents of the fuel on the superheater surface temperatures (steam temperatures) in steam boilers is given. Furthermore, it has to be taken into account, that increasing S and Cl concentrations in the flue gas result in a change of the dew point of the flue gas, which has to be considered concerning possible condensation in the heat exchangers and the flue gas cleaning systems.

Figure 6 exemplary shows how the chemical composition and the ash content of different solid biomass fuels can vary. The ash contents for bark and waste wood are high and even higher for straw while the ash content of pure wood fuels is comparably low. The sulphur content is high in straw and waste wood. The lowest sulphur contents are found in wood chips. The chlorine and potassium content of herbaceous fuels is considerably higher than of woody biomass fuels, which directly affects aerosol formation and ash melting. The big deviations between different biomass fuels concerning their contents of ash forming elements clearly underlines the

relevance of considering the fuel specific properties during plant design.

Figure 7 shows relevant guiding parameters which can be derived from the chemical compositions of different solid biomass fuels. An important guiding parameter is the molar ratio $(K+Na) / (2S+Cl)$. During combustion S and Cl preferably form alkaline (K and Na) sulphates and chlorides (S also forms Ca and Mg sulphate). Cl and S, which are not bound by these elements, form gaseous emissions, namely HCl and SO_x . A molar ratio of $(K+Na)/(2S+Cl) > 1$ indicates a surplus of alkaline metals. Therefore, for high molar ratios of $(K+Na)/(2S+Cl)$ lower HCl and SO_x emissions have to be expected, since most of the S and Cl is expected to be bound in the ash.

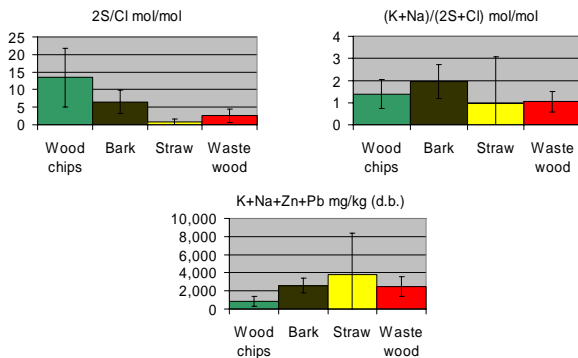


Figure 7: Chemical compositions of different solid biomass fuels – relevant guiding parameters

A molar ratio of $2S/Cl > 1$ indicates an increased formation of alkaline sulphates, whereas a molar ratio of $2S/Cl < 1$ indicates the preferred formation of alkaline chlorides. As corrosion related problems on heat exchanger surfaces are depending on the Cl content of the ash deposits, a low molar ratio of $2S/Cl$ increases the risk of corrosion.

The elements K, Na, Zn and Pb are the most relevant aerosol forming elements in biomass fuels. With increasing concentration of these elements in a biomass fuel the probability of the release of ash forming elements during combustion rise and therefore aerosol formation as well as deposit formation increase as well. However, the formation of ash vapours during combustion is not proportional to the concentration of these elements in the fuel since chemical reactions with other elements (e.g. Si) as well as the gaseous atmosphere and the combustion temperature significantly influence the release behaviour.

ASH FORMATION AND ASH RELATED PROBLEMS

As already mentioned, ash related problems in biomass combustion processes are always strongly associated with the fuel chemistry, in detail with the concentration and speciation of inorganic compounds in the fuel. Therefore, if an ash related problem has to be evaluated always comprehensive knowledge about the fuel is needed. Solid biomass fuels, which are presently utilised in combustion processes can be categorised as follows:

- Chemically untreated wood fuels (wood chips, sawdust, wood pellets, bark etc.)
- Waste wood
- Wood from short rotation forestry
- Straw

- Biogenic agricultural and industrial residues (e.g. kernels, shells, olive residues, residues from liquid biofuel production etc.)

Ash and aerosol formation and their impact on combustion technology

During the combustion of solid biomass fuels, the behaviour of ash forming elements follows a general scheme, which is depicted in Figure 8. The following gives a brief description of the basic principles of ash formation during biomass combustion.

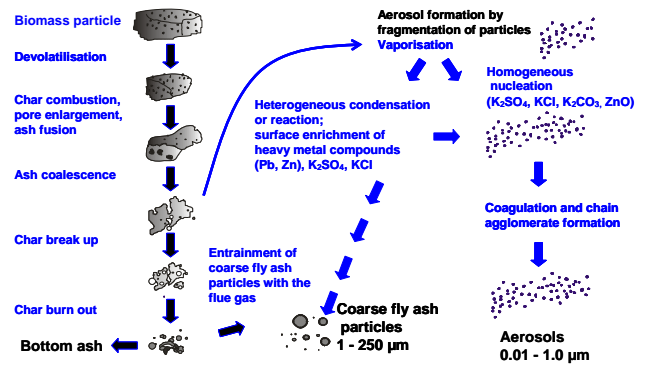


Figure 8: Ash formation during biomass combustion

Upon entering the combustion unit, the fuel is first dried, followed by devolatilisation of the volatile organic matter. Subsequently, the remaining fixed carbon is oxidised during heterogeneous gas-solid reactions, which is called charcoal combustion. During these steps the ash forming elements behave in two different ways depending on their volatility. Non-volatile compounds such as Si, Ca, Mg, Fe and Al are engaged in ash fusion as well as coagulation processes. Once the organic matter has been released or oxidised, these elements remain as coarse ash structures. Easily volatile species such as K, Na, S, Cl, Zn and Pb generally behave differently. A considerable proportion of these elements is released to the gas phase due to the high temperatures occurring during combustion. There they undergo homogeneous gas phase reactions and later, due to supersaturation in the gas phase, these ash forming vapours start to nucleate (formation of submicron aerosol particles) or condense on respectively react with the surfaces of existing particles or directly condense on heat exchanger surfaces. The submicron particles, so-called aerosols, form one important fraction of the fly ashes. The second fly ash fraction consists of small coarse ash particles entrained from the fuel bed with the flue gas. Depending on particle size, they are either precipitated from the flue gas in the furnace or boiler mainly by inertial impaction or gravitational settling, or are entrained with the flue gas, forming coarse fly ash emissions. Consequently, the most relevant difference between coarse fly ashes and aerosols is that coarse fly ashes always remain in the solid phase while aerosols undergo phase changes during their formation process (release to the gas phase and gas-to-particle conversion).

It is also important to mention that a share of the volatile ash forming elements is not released to the gas phase but undergoes secondary reactions with the non-volatile species (e.g. Ca, Si), thus being embedded in the coarse ash. The mechanisms of these secondary reactions and the parameters influencing the release of volatile species from the fuel are of great relevance for aerosol and deposit formation and are therefore a major issue in research projects [9].

Especially with respect to the utilisation of herbaceous biomass fuels as well as residues from agricultural, food and biofuel industry the special role of P has to be mentioned. In conventional wood fuels P is mainly inorganically bound and therefore, almost all P is embedded in the coarse ash fraction. In agricultural biomass as well as biogenic residues from industrial processes a share of the P may also be organically bound. Parts of this organically bound P can also be released to the gas phase and therefore participate in aerosol and deposit formation processes [8,10].

The *bottom ash* represents the ash fraction remaining in the furnace after combustion of the fuel and is then removed by the de-ashing system. *Coarse fly ash* particles which are entrained from the fuel bed with the flue gas are partly precipitated on their way through the furnace and the boiler by inertial impaction, gravitational and centrifugal forces and therefore form the so-called *furnace* or *boiler ash*. Particles which are small enough to follow the flue gas on its way through the furnace and the boiler finally form the *coarse fly ash emission* at boiler outlet. The major share of these particles is precipitated in cyclones or filters and forms the *cyclone fly ash* and parts of the *filter fly ash*.

Table 4: Typical shares of the different ash fractions on the total ashes produced

	bark combustion	wood chips combustion	sawdust combustion	straw combustion
bottom ash	65 - 85	60 - 90	20 - 30	80 - 90
cyclone fly ash	10 - 25	10 - 30	50 - 70	2 - 5
filter fly ash	2 - 10	2 - 10	10 - 25	5 - 15

In Table 4 typical data concerning the fractionation of ashes into bottom ashes, cyclone fly ashes and filter fly ashes in modern fixed-bed biomass combustion plants are presented [11]. On the contrary, in fluidised bed and pulverised fuel combustion the amount of bottom ash is low while the fly ash fractions clearly dominate. It is recommended to use a two-stage fly ash precipitation (cyclone plus filter) in order to increase the overall dust precipitation efficiency.

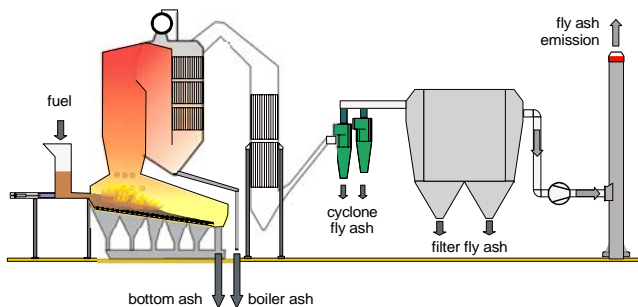


Figure 9: Ash fractions in a biomass combustion unit
Explanations: typical plant scheme of a large-scale grate-fired steam boiler

As already mentioned, *aerosols* are formed by gas-to-particle conversion processes in the furnace and in the boiler. Some of the aerosol particles coagulate with coarse fly ashes due to collisions. Moreover, a smaller part of aerosols is also precipitated in the boiler and therefore contributes to the boiler ash while the major part of this fraction is emitted with the flue gas at boiler outlet. Since aerosols are characterised by particle sizes significantly $<1 \mu\text{m}$ (ae.d.), precipitation in a cyclone, which usually has a cut diameter of about 5 to 10 μm , is almost impossible. Aerosols can thus only be

precipitated in more advanced filter systems such as baghouse filters and electrostatic precipitators (ESP). Consequently, aerosols do not contribute to the cyclone fly ashes but to the filter fly ashes as well as to the particulate emissions at the filter outlet.

In Figure 9 the scheme of a typical large-scale grate-fired steam boiler is presented to show where the different ash fractions occur.

A considerable number of tests has been carried out to investigate possible parameters which could influence the mass of aerosols formed during combustion. Therefore, the combustion air ratio, the furnaces temperature, the moisture content of the fuel as well as the influence of flue gas recirculation were considered. These parameters were varied during test runs in a range, which is typical for the operation of fixed-bed combustion units. From the evaluation of these tests no significant influences of the parameters mentioned on the mass of aerosols formed during combustion could be identified. This leads to the conclusion that as long as almost complete burnout prevails, the fuel composition, or in more detail, the release of aerosol forming species from the fuel during combustion, is the most relevant parameter which determines the mass of aerosols formed.

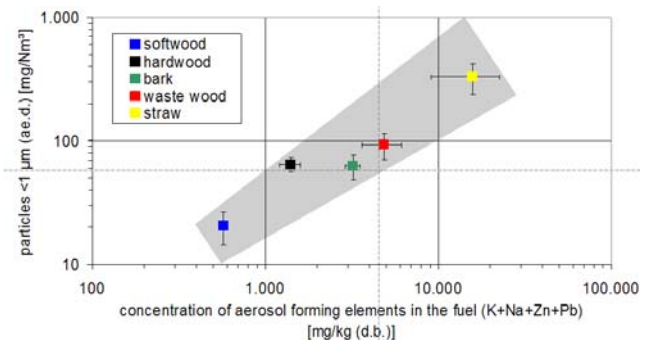


Figure 10: Influence of the fuel used on the mass of aerosols formed

This statement is confirmed by the data presented in Figure 10, where the concentrations of the most relevant aerosol forming elements K, Na, Zn, and Pb in the fuel are plotted against the average aerosol emissions measured at boiler outlet of medium and large-scale fixed-bed combustion plants [12].

Results from test runs including element balances over fixed-bed combustion plants performed with beech, bark and waste wood have shown that usually 10 - 90 wt% of K, more than 80% of S, more than 95% of Cl as well as more than 80% of Zn and Pb are released to the gas phase.

With decreasing burnout quality of the flue gas, aerosol emissions also contain differing amounts of carbonaceous species (organic carbon and soot). Organic carbon and soot emissions are of relevance in small-scale combustion units and older plants. In state-of-the-art medium and large-scale combustion systems almost complete burnout is achieved and aerosol emissions almost exclusively consist of inorganic compounds.

The basic mechanisms of aerosol formation in combustion processes are generally well known from previous research work [13,14]. As already mentioned, aerosols are formed by nucleation of ash forming vapours. The particles subsequently grow by condensation of vapours on their surfaces as well as by coagulation processes.

Figure 11 shows SEM images and results from EDX analyses of aerosols. It can be derived that aerosols consist of almost spherically shaped particles and agglomerates thereof,

which is typical for particles formed by nucleation and subsequent coagulation.

K, Na, S and Cl are the most relevant aerosol forming species in the specific case of chemically untreated wood combustion. Consequently, the formation of K and Na sulphates and K and Na chlorides followed by nucleation of these compounds are the most relevant processes leading to aerosol formation. The molar ration of S/Cl strongly influences sulphate and chloride formation. Aerosols from straw combustion are strongly dominated by KCl (see Figure 12). Carbonates are formed if there is not enough S and Cl available to bind all the K and Na released from the fuel.

Additionally, easily volatile heavy metals such as Zn and Pb may significantly contribute to aerosol formation, especially with increasing concentration of these elements in the fuel. Aerosols formed during the combustion of waste wood (which is very rich in heavy metals), for instance, may contain more heavy metal compounds than alkaline compounds [15,16,17]. Zn mainly forms oxides and chlorides and Pb chlorides. This behaviour is confirmed by the results of the EDX analyses presented in Figure 11.

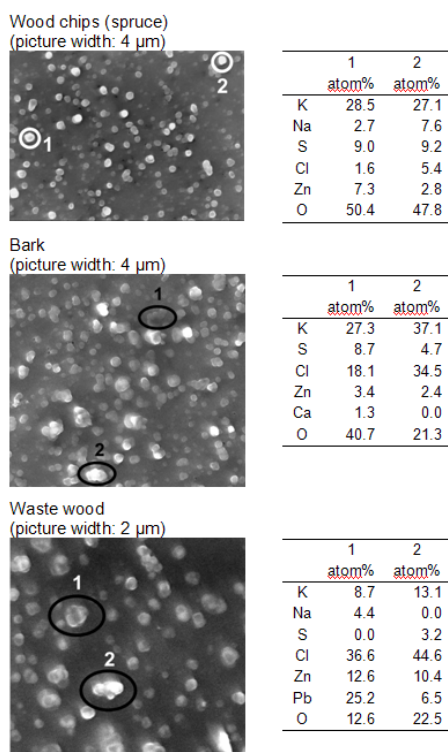


Figure 11: SEM images and results from EDX analyses of aerosols

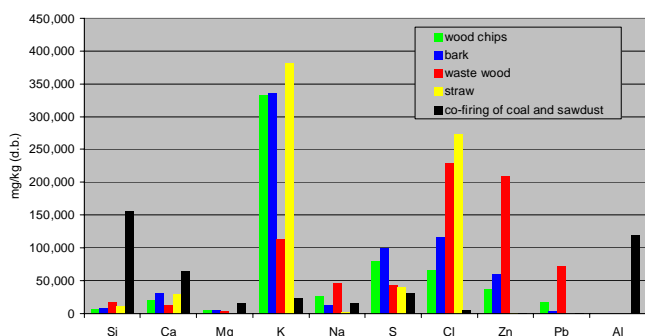


Figure 12: Typical compositions of aerosols from biomass combustion and co-firing of biomass (sawdust)

Explanations: Data related to dry flue gas and 13 vol.% O₂; results from real-scale test runs

Non-volatile elements like Ca and Si can also be found to a certain extent in aerosols due to defragmentation processes during combustion or direct release from the organic matrix (or the cell solution) during decomposition. When cofiring biomass with coal completely different chemical composition of aerosols dominated by aluminosilicates and CaSO₄ occur (due to the different chemical composition of coal and the higher combustion temperatures in entrained coal flames, see Figure 12). The chemical composition of the fuel strongly dominates the amount and chemical composition of the aerosols formed which is relevant regarding their stickiness and corrosiveness (see next sections). Especially for new biomass fuels and fuel blends aerosol characterization and measurements are very important. To gain appropriate data regarding aerosol formation in biomass combustion systems, a unique high-temperature impactor that can operate at temperatures up to about 1,100°C is available [18,19].

Slagging, deposit formation and corrosion and their impact on combustion technology

Ash melting, deposit formation and corrosion are the major internal plant operation related problems which are associated to ash forming elements. Ash melting can occur on the grate and on non-cooled furnace walls. Moreover, fly ash depositions formed on heat exchanger surfaces can also melt. As soon as ashes start partly to melt or fuse, the resulting ash pieces are usually called slag.

Deposit formation means the formation of ash layers on furnace and boiler surfaces (furnace walls, radiative and convective heat exchanger surfaces). Thereby it is often distinguished between slagging and fouling. Slagging is the formation of molten or partially fused deposits on furnace walls or convection surfaces exposed to radiant heat. Fouling is commonly defined as the formation of deposits on convective heat exchanger surfaces such as boiler tubes in hot water fire tube boilers and superheaters in water tube steam boilers.

Ash melting on the grate can result in problems with the combustion process since slag plates can hinder the primary air flow through the fuel bed. Moreover, larger slag pieces can lead to damages of the grate as well as to problems with blocking the de-ashing system. Slagging in the furnace can lead to increased pressure losses due to smaller flow areas in narrow parts of the furnace and slagging in the radiative sections of steam boilers can lead to reduced heat transfer. In Figure 13 typical examples for slagging on a grate and for slag formation in the radiative part of a steam boiler are presented.



Figure 13: Examples for slag formation

Explanations: left: slag formation in a moving grate furnace during combustion of industrial biogenic residues; right: slag formation in the radiative section of a steam boiler

Slag formation in biomass furnaces and boilers is always a result of ash melting. Not necessarily the whole ash has to melt. Usually, single phases which show low melting

temperatures start to melt and act as glue between ash particles with higher melting temperatures. Therefore, always different phases of molten and non-molten compounds can be found when analysing slag pieces or hard deposits. According to practical experiences and literature [20] the formation of slag pieces and hard deposits starts at temperatures where 15 wt% of the ash in a certain ash piece are molten (T_{15}). At the temperature where the share of molten phases exceeds 70 wt% (T_{70}), the slag/deposit starts to flow.

Thermodynamic equilibrium analyses have turned out to be a useful tool to evaluate the melting behaviour of biomass ashes. Thereby, thermodynamic calculations of multi-phase and multi-component systems which simultaneously can handle hundreds of chemical species are applied. For combustion systems both major and minor ash forming components must be taken into account. The reactions of the minor components are usually dependent on the reactions of the major components. However, minor elements, especially Pb and Zn as well as Cl are also of great relevance, since they contribute to a reduction of the ash melting temperatures of ash mixtures (see Figure 15). It has to be mentioned that the thermodynamic databases used must be of high quality. Small errors and deviations in data for main components give bigger errors on small components and give wrong results. In this respect, it has to be mentioned that especially concerning systems containing P only restricted thermodynamic data are presently available.

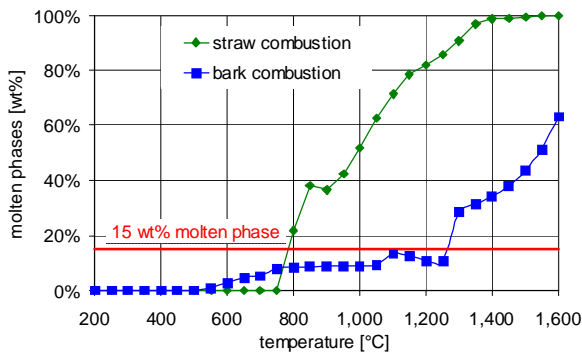


Figure 14: Formation of molten phases – results from thermodynamic equilibrium analyses

Explanations: results of thermodynamic equilibrium calculations concerning the bottom ash

One big advantage of thermodynamic equilibrium analyses is that they can be performed for typical grate ash as well as fly ash compositions separately. Therefore, also the significantly differing chemical composition of these fractions can be taken into account when determining their melting behaviour (e.g.: fly ashes with high amounts of alkaline metal salts show lower melting temperatures).

In Figure 14 results from thermodynamic equilibrium analyses performed for bottom ashes from bark and straw combustion are presented. In the diagram the amount of molten phase in the ash is plotted against the temperature. Since the input data for the calculations have been taken from bottom ash analyses performed during real-scale test runs, realistic ash compositions form the basis for these calculations, which is one of the big advantages of this method. From the diagram it can be derived that in the case of straw combustion a rapid increase of the molten phases at temperatures above 750°C occurs. T_{15} is reached below 800°C. For ashes from bark combustion this effect happens at significantly higher temperatures of about 1,250°C. Moreover, the results of the calculations provide data about

the compositions of the molten phases as well as the changes of the compositions depending on temperature. These results can then also be compared with results from SEM/EDX analyses of molten phases of ash and slag pieces in order to get a more detailed picture of the ash melting behaviour of complex ash mixtures. Thus such calculations can be very useful to indicate relevant trends and differences between various fuels and ash fractions and form a useful tool for advanced fuel characterisation.

In Figure 15 the influence of heavy metals on the melting behaviour of Cl-containing fly ash mixtures is presented. The blue line for instance shows a typical biomass fly ash which often is almost pure K_2SO_4 (melting point: 1,068°C). If carbonate is formed the first melting point decreases to 940°C, and if chlorides form the first melting point decreases to 643°C. Small amounts of Na (red curve) decrease the first melting point to 609°C. The presence of Pb and Zn, even in small amounts compared to K and Na, results in molten phases at such low temperatures as 196°C.

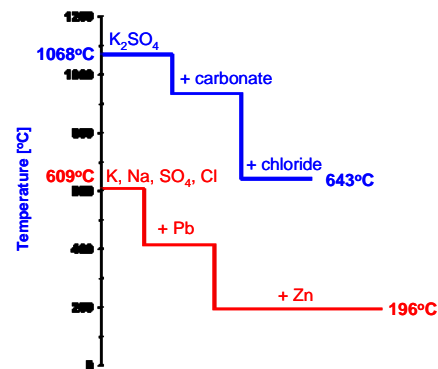


Figure 15: The influence of heavy metals on the melting temperatures of Cl-containing ash mixtures

Explanations: source: [9]

As it can be revealed from Figure 14 and Figure 15, ashes from different biomass fuels can show significantly different ash melting behaviours and therefore, measures to reduce problems with ash melting and slagging in combustion plants have always to be adjusted to the chemical composition of the fuel applied. Appropriate measures usually implemented in modern biomass combustion systems are grate cooling, furnace cooling by cooled walls or flue gas recirculation, the appropriate adjustment of the flue gas inlet temperatures in convective boiler sections and of the superheater steam temperatures as well as the utilisation of additives (see also next section).

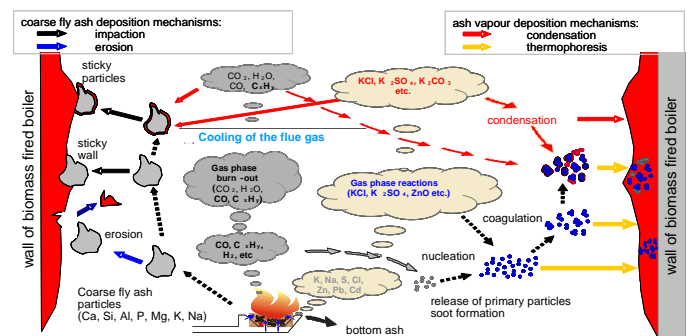


Figure 16: Mechanisms of deposit build-up in biomass fired boilers

Deposits are formed by coarse fly ashes as well as condensable gaseous ash forming compounds present in the flue gas. Under the typical conditions prevailing in biomass

hot water, thermal oil and steam boilers, the direct condensation of ash forming vapours on heat exchanger surfaces and inertial impaction are of major relevance concerning deposit formation. Thermophoresis also plays a certain role while other mechanisms such as turbulent eddy impaction, Brownian diffusion and diffusiphoresis are of minor relevance (see Figure 16).

With increasing deposit thickness the heat transfer through the heat exchanger tubes decreases which results in a loss of efficiency. Severe deposit formation (fouling) can block the flue gas pathways through heat exchanger sections. In Figure 17 deposits on superheater tubes of a waste wood fired steam boiler are presented.

It has to be considered that the temperature at the gas side deposit surface increases with increasing deposit thickness, which is illustrated in Figure 18. There, results gained from CFD simulations performed for a superheater tube with a surface temperature of 590°C which is exposed to a flue gas stream with 1,050°C are presented. From the simulation results it can be derived that with increasing deposit thickness the surface temperature at the flue gas side significantly increases and finally reaches more than 900°C at a deposit thickness of about 4 mm. With increasing surface temperature also the fraction of molten phases increases and therefore the deposit becomes more sticky and grows faster. Finally, higher amounts of molten phases also lead to the formation of hard deposit layers which are problematic to be removed.

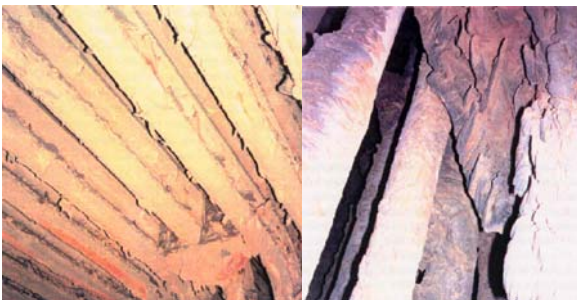


Figure 17: Pictures of deposits formed on superheater tubes of a steam boiler during waste wood combustion

Explanations: left: typical deposit formation; right: severe deposit formation leading to the blocking of heat exchanger pathways

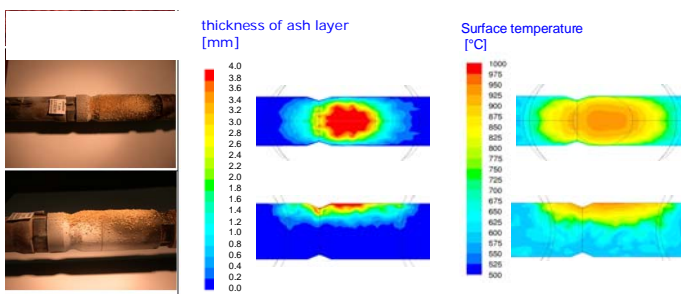


Figure 18: Ash deposit layer on a water-cooled deposition probe (left) compared with CFD simulations performed (middle) and influence of ash depositions on the surface temperatures (right)

Explanations: bulk flue gas temperature: 1,050 °C, clean probe surface temperature: 590 °C; figures at the top ... top view; figures at the bottom ... side view

Consequently, it is important to periodically clean heat exchanger surfaces in order to reduce deposit growth. Therefore, different automatic heat exchanger cleaning systems listed in the following are usually applied.

Fire tube boilers can be cleaned by injecting pressurised air into the tubes. Thereby, in an interval of some hours for some milliseconds an air pulse is injected which cleans the

boiler tubes. The air pulse is controlled by membrane valves. To protect these valves from too high temperatures, the cleaning system is usually installed on the wall of the turning chamber between the first and the second duct (cleaning of the first duct in counter-current and of the second duct in co-current flow).

In water tube steam boilers usually soot blowers are installed to remove deposits from the superheater surfaces. If there is an increased risk for deposit formation on the tubes in the radiative boiler section, sometimes also water canons are installed. Moreover, shot cleaning by injecting small metal balls into the heat exchanger bundles is sometimes applied.

Besides these secondary measures also primary measures for the reduction of deposit formation should be considered. These measures involve the adjustment of the flue gas and tube surface temperatures to the expected properties of condensing ash forming compounds (which depend on the composition of the fuel applied) during boiler design as well as a careful control of the flue gas temperatures during operation. Moreover, additives can be used to reduce deposit formation (see next section).

Additionally, it should be mentioned that load changes can lead to changing flue gas and boiler tube temperatures. Due to thermal stresses, deposits can be partly destroyed during phases with load changes. This effect can additionally support the efficiency of automatic cleaning systems.

Corrosion is an important issue especially for biomass plants utilising fuels with high chlorine contents. For biomass combustion generally three possible corrosion mechanisms must be distinguished:

- Active oxidation
- Corrosion due to molten alkaline metal compounds and other salts
- Acid dew point corrosion

The so-called active oxidation is the most relevant corrosion mechanism in biomass boilers. The mechanism is based on the formation of Cl-containing deposit layers on the boiler tube surfaces. The first step of deposit formation is the formation of an ash layer by direct condensation of alkaline metal and heavy metal salts (chlorides and sulphates) on the boiler tube surfaces. The chemical composition of this condensed layer depends on the tube surface temperature and on the fuel composition respectively the release behaviour of alkaline metals, Cl, S and easily volatile heavy metals from the fuel to the gas phase. If the molar ratio 2S/Cl released from the fuel to the gas phase is high and flue gas temperature above 850°C occur, mainly alkaline metal sulphate vapours are formed while, if this ratio is low, the formation of alkaline metal chlorides usually dominates.

N_2, CO_2, O_2	flue gas	SO_2, O_2
$SO_2, SO_3, MeCl (g)$		
sulfates/chlorides	ash layer	$Cl_2 + Na_2SO_4 \leftarrow SO_2 + O_2 + 2 NaCl$
silicates		
$Fe_2O_3 + ash$	outer oxide layer	
$Fe_3O_4 + FeS$	inner oxide layer	$3 Fe_2O_3 \leftarrow 1/2 O_2 + 2 Fe_3O_4$
$FeCl_2$	corrosion front	$3 Cl_2 + Fe_3O_4 \leftarrow 2 O_2 + 3 FeCl_2$
		$4 Cl_2 + FeS + Fe_3O_4 \leftarrow SO_2 + O_2 + 4 FeCl_2$
		$Cl_2 + Fe \rightarrow FeCl_2$
low alloyed steel	tube wall	$p_{FeCl_2} = 10^{-5} \cdot 10^{-3} \text{ bar at } 400 - 530 \text{ }^\circ\text{C}$

Figure 19: Schematic explanation of the active oxidation mechanism [21]

Combustion tests with chemically untreated wood fuels as

well as waste wood, performed have shown, that, when utilising chemically untreated biomass, at tube surface temperatures above 500°C the Cl concentration in the deposits starts to significantly decrease [17]. As soon as the surface temperature exceeds 550°C almost no Cl could be found in the deposits. Superheaters of modern steam boilers utilising chemically untreated biomass fuels are usually designed for steam temperatures between 480 and 540°C and thus operate in this temperature range.

In hot water boilers on the other hand, where the tube surface temperatures are rather low (around 100°C) compared with steam boilers, Cl containing deposits are found even when utilising fuels with very low Cl contents and high 2S/Cl ratios.

To start the process of active oxidation besides Cl-containing deposits also gaseous SO₂ is needed. SO₂ reacts with alkaline metal chlorides under formation of alkali metal sulphate and release of Cl₂. This process happens in the deposit layer and therefore, Cl₂ diffusing towards the inner oxide layer can form FeCl₂. FeCl₂ has, depending on the temperature, a certain volatility under reducing conditions and can therefore be vaporised. The vapour formed diffuses from the tube wall into the ash layer. There, it is oxidised again (due to the increasing partial pressure of O₂ towards the flue gas) and the Cl₂, which is released, can diffuse back to the tube wall and react there again with iron oxide. Following this process, even small amounts of Cl released in the ash layer have the potential to cause considerable corrosion damages if the residence time of the ash layer on the tube surfaces is high enough.

Three measures to reduce active oxidation can be mentioned:

- Utilisation of fuels with a high 2S/Cl ratio to enforce the formation of K₂SO₄ instead of KCl layers.
- Lower tube surface temperatures considerably reduce the evaporation of FeCl₂ and thus slow down the corrosion process.
- Frequent cleaning of the boiler tubes (implementation of automatic boiler cleaning systems) in order to keep the residence time of ash layers on the tube surfaces low and thus to limit the sulphation reactions.

Also the second corrosion mechanism depends on the presence of alkaline metal and heavy metal chlorides and sulphates on boiler tube surfaces. These chlorides and sulphates and especially mixtures of them can show comparably low melting temperatures (see also Figure 15). Molten salt phases thereby can attack the tube material. This mechanism is of minor relevance for the combustion of chemically untreated fuels. However, in the case of the combustion of waste material such as waste wood, which contains comparably high heavy metal concentrations, it can be of relevance.

During the utilisation of chemically untreated woody biomass fuels usually no problems with acid dew point induced corrosion are observed. However, when utilising waste wood or biogenic residues, this mechanism can become important. If a fuel contains high S- concentrations and comparably low K and Ca-concentrations, a relevant amount of S will not be embedded into the ashes by the formation of K₂SO₄ and CaSO₄ but remain as SO₂ in the gaseous phase. A part of the SO₂ reacts to SO₃ and then with water (flue gas moisture) to H₂SO₄. The acid dew point temperature (ADT) of H₂SO₄ significantly increases with increasing SO₃ concentrations in the flue gas. If the

temperatures of boiler or economiser tube surfaces are below this dew point temperature, H₂SO₄ condensation followed by corrosion takes place. Therefore, an appropriate adjustment of the surface temperatures of economisers and hot water boilers beyond the expected acid dew points is of relevance.

For future technological developments the main aim is to increase the thermal and electric efficiency by increasing the steam parameters. Thereby, especially fouling and corrosion related problems have to be considered. For straw combustion for instance, a steam temperature of 542°C leading to an electric efficiency of 31.7% has already been achieved in the CHP plant Maribo-Sakskøbing (Denmark) as well as in other plants. Figure 20 shows a scheme of this CHP plant which utilises wheat straw and has implemented appropriate technological solutions in order to reduce corrosion particularly in the high temperature stages of the superheaters. The boiler and in particular the superheaters are specially designed to handle the harsh condition from combustion of straw and straw-like biomass fuels in a highly efficient boiler with advanced steam data. The first and second pass superheater stages are operated in the so-called slagging mode. A continuous K₂SO₄ slag layer on tube surfaces protects the super heater material against high temperature chlorine corrosion. The slag layer is several cm thick and is only removed when the plant is shut down due to thermal stress. By this way electric efficiencies of more than 31% can be achieved in medium-scale CHP plants at plant availabilities of above 90%.

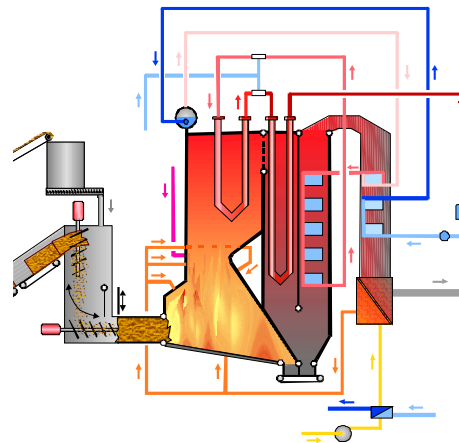


Figure 20: Case study for appropriate technological solutions in order to reduce ash related problems – the CHP plant Maribo-Sakskøbing (Denmark)

Explanations: source: Bioener ApS; main fuel: wheat straw; steam pressure: 92 bar; steam temperature: 542 °C; power output (gross) 10.6 MW; thermal output: 20 MW; electric efficiency (gross): 31.7 %; thermal plant efficiency: 60 %; total plant efficiency: 91.7 %

For CHP plants utilising woody biomass fuels, even higher steam parameters and consequently efficiencies should be the target for future developments. First R&D results show low corrosion potentials due to decreasing Cl-concentrations in deposits at temperatures above 540°C but further long-term tests are needed. For such tests especially newly developed corrosion probes are an useful development tool [22,23]. The correct choice of the superheater materials of course plays an important role for such advanced approaches. Moreover, the application of additives which reduce the Cl-content of deposits (e.g.: “Chlorout”, see next section) can contribute to a further increase of the steam temperatures.

Additives to reduce ash related problems

During recent years a considerable number of studies has been performed in order to investigate the effects of different additives on ash melting and corrosion in biomass boilers. The studies mainly focused on the reduction of ash melting problems as well as on reducing the formation of KCl and NaCl rich deposits. Therefore, several strategies can be distinguished.

The first strategy is to bind the K in the bottom ashes and thereby to reduce the formation of alkaline metal vapours and consequently also aerosol and deposit formation. A well known "alkaline metal catcher" for instance is Kaolin. By adding Kaolin to the fuel, K is embedded into Si-Al-phases of the bottom ashes [24, 25]. However, due to its high costs no industrial applications of Kaolin as alkaline catcher are known so far. The same effect can be achieved by blending an alkaline and Cl-rich biomass fuel with coal, peat or sewage sludge. Also in this case the Si-Al-rich phases of the bottom ashes help to significantly reduce the K release and consequently the formation of KCl. This strategy is already successfully applied in many biomass co-firing plants as well as in large-scale Finish biomass power plants, where, due to the high local availability of peat, mixtures of biomass and peat are utilised.

Purpose	Additive	State-of-application
Alkaline metal catchers to reduce aerosol formation	Kaolin	R&D
Sulphation of chlorides to reduce corrosion	ChlorOut (ammonium sulphate)	Demonstration
Additives to increase ash melting temperatures	Ca-based Mg-based	R&D
Additives to reduce SO ₂ -HCl- and PCDD/F-emissions	Limestone Sodium bicarbonate Activated charcoal	State-of-the-art

Figure 21: Additives which can be applied in biomass combustion plants in order to reduce ash related problems

The second strategy is to enforce the conversion of the problematic KCl into less problematic K₂SO₄. Therefore, Vattenfall AB (SWE) has developed an additive called Chlorout® [26]. Chlorout® consists of Ammoniumsulphate which is injected directly into the hot furnace. There it decomposes to ammonia and SO₃ and with the SO₃ KCl is sulphated in the gas phase before it starts to condense. As a consequence of this sulphation reaction, the concentration of KCl in deposits can be significantly reduced. Moreover, the rate of deposit build-up is reduced since the K₂SO₄ formed by the sulphation of the KCl partly forms submicron aerosol particles in the furnace by nucleation and condensation, and therefore the direct condensation of alkaline vapours on the superheater surfaces is reduced. The ammonium sulphate injection is thereby controlled by an in-situ alkali chloride monitor (IACM), which has also been developed by Vattenfall AB. Test and demonstration of additivation with Chlorout® are ongoing in several biomass and waste fired CHP plants [27].

Moreover, Ca and Mg-based additives can be applied in order to increase the ash melting temperature of low-melting ash mixtures. This strategy is of special relevance for the application of agricultural biomass fuels and industrial biogenic residues since these fuels are usually rather poor in Ca and Mg but show low melting temperatures due to high K and P contents.

In order to reduce SO₂- and HCl-emissions limestone or sodium bicarbonate in combination with a baghouse filter are used. Activated charcoal can be added to also reduce PCDD/F emissions. This technology should be applied for fuels with high Cl and S contents as well as in combination with Chlorout® (to reduce increased HCl emissions).

GASEOUS EMISSIONS UNDER SPECIAL CONSIDERATION OF NO_x

CO₂ is a major combustion product from all biomass fuels, originating from the carbon content in the fuel. However, CO₂ emissions from biomass combustion are regarded as being CO₂-neutral with respect to the greenhouse gas effect and this is considered to be the main environmental benefit of biomass combustion.

Carbon monoxide emissions are caused by incomplete combustion which are mainly a result of inadequate mixing of combustion air and fuel in the combustion chamber, an overall lack of available oxygen, too low combustion temperatures and too short residence times. Incomplete combustion is however usually not an issue for state-of-the-art combustion plants.

NO_x emissions from biomass combustion applications are mainly a result of complete oxidation of fuel nitrogen, both from gas-phase combustion and char combustion. Additional NO_x may be formed from nitrogen in the air given certain conditions. However, these reaction mechanisms are not considered to be of significant importance in most biomass combustion applications due to the limited combustion temperatures. The main nitric oxide emitted is NO, which is converted to NO₂ in the atmosphere.

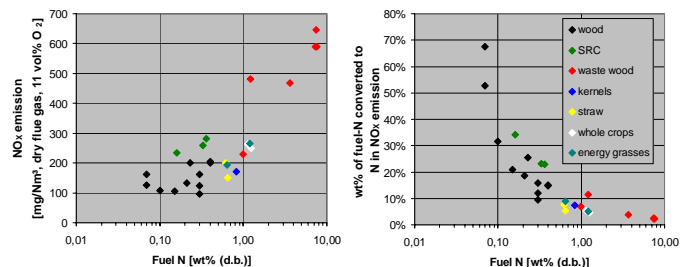


Figure 22: NO_x emissions (left) and fuel N converted to NO_x (right) in dependence of the N content in the fuel for different biomass fuels

In Figure 22 measured data of NO_x emissions (left) and the percentage of fuel N converted to NO_x (right) versus the N content in the fuel are shown for different biomass fuels. The figure clearly indicates that NO_x emissions increase with increasing N content in the fuel while the rate of fuel N converted to NO_x decreases.

In Figure 23 conversion rates of N species related to the total fixed nitrogen (TFN) formed which have been derived from tests in a lab-scale reactor for different woody biomass fuels and olive residues are depicted [28]. The dominance of NH₃ is obvious. NO represents the most important oxidised N species for woody biomass fuels. For chopped herbaceous biomass fuels different N species profiles occurred. NO represents the largest fraction among the N species released. Experimental data about conversion rates of N species form an important basis for subsequent CFD simulations of NO_x formation in biomass combustion plants (see also next section).

In order to reduce NO_x emissions from biomass combustion, several primary and secondary measures exist.

For the utilisation of chemically untreated biomass fuels, secondary measures are normally not necessary [11,29]. If secondary measures are necessary, they should always be combined with primary measures in order to efficiently utilise the NO_x reduction potential available and to reduce operating costs (additive utilisation).

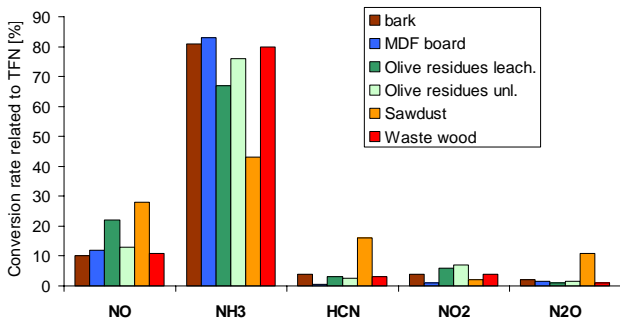


Figure 23: Conversion rates of N species related to TFN of woody biomass fuels and olive residues

Explanations: TFN...total fixed nitrogen (sum of NO, NH₃, HCN, NO₂ and N₂O); leach...leached; unl...unleached

Air staging is a widely applied primary measure for NO_x reduction where primary and secondary combustion air are injected in separated zones. In order to efficiently reduce NO_x emissions, the air ratio in the primary combustion chamber should be between 0.6 and 0.8 and the residence time of the flue gas in the primary combustion chamber approx. 0.2 to 0.5 s at temperatures above 800 °C. Furthermore, good mixing in the primary combustion zone is of great relevance which can be achieved by appropriate flue gas recirculation. The potential for NO_x-reduction by air staging is 30 to 60%.

A second possibility to reduce NO_x emissions by primary measures is fuel staging, where the primary and the secondary fuel is supplied in separate zones. Due to the complexity of the system, fuel staging is usually limited to large-scale applications. Approx. 70% primary fuel and 30% secondary fuel is used. The excess air ratio in the reduction zone following the secondary fuel supply should be between 0.6 to 0.8. Natural gas, biomass producer gas, shavings or sawdust are usually utilised as secondary fuels. The potential of NO_x reduction by fuel staging amounts to 50 to 70%.

If primary measures fail to achieve the targeted NO_x reduction, they can be combined with secondary measures. These are selective non-catalytic reduction (SNCR) and selective catalytic reduction (SCR) [11,30].

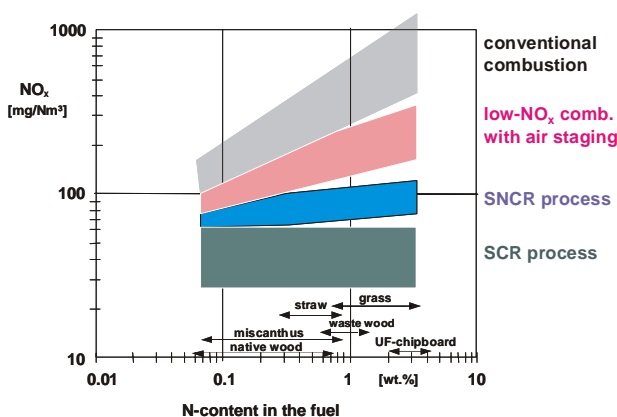


Figure 24: Relation between fuel N content, NO_x emission reduction measures and NO_x emissions

Explanations: NO_x calculated as NO₂ and related to dry flue gas and 11 vol.% O₂

In the SNCR process, ammonia or urea is injected into the flue gas at high temperatures, usually between 840 and 950°C and a residence time after injection of 0.3 to 0.5 s [30]. Because of the high temperature, this process does not need a catalyst to initiate the reactions. Ammonia is injected at a rate of between 1:1 to 2:1 mole ammonia to mole of NO_x reduced. About 60-90% NO reduction can be reached with SNCR. The SNCR process requires an accurate temperature control to achieve optimum NO_x reduction conditions. If the temperature is too high, ammonia is oxidised to NO and if the temperature is too low, ammonia does not react at all and is emitted together with the NO_x. Good mixing is very important to achieve optimum NO_x reduction conditions. Most SNCR processes have an ammonia slip of some ppm in the flue gas leaving the stack.

The SCR process reduces NO to N₂ by reactions with usually ammonia or urea in the presence of a platinum, titanium, or vanadium oxide catalyst. SCR operates optimally in a temperature range of 220-270°C using ammonia, and 400-450°C using urea [30]. The stoichiometric coefficient is usually around 1.0. Approximately an 80% NO_x reduction has been reported for SCR in fossil fuel combustion [31], where it is the most widely used secondary NO_x control technology. However, Nussbaumer [30] reported up to 95% NO_x reduction at 250°C without significant slippage of ammonia in a wood-firing system. For the SCR process in combination with biomass combustion, the long-term behaviour of the catalyst can be a problem, as deactivation is likely. In this respect, an efficient dust precipitation stage upstream the SCR unit is an important requirement. SCR systems are considerably more expensive than SNCR systems but can be economically interesting for large-scale applications due to the better conversion efficiency achievable.

Figure 24 shows the relation between fuel N content, NO_x emission reduction measures and NO_x emissions.

CFD AS AN EFFICIENT TOOL TO DESIGN AND OPTIMISE BIOMASS COMBUSTION SYSTEMS

Modern simulation tools are needed to efficiently analyse the underlying processes during biomass combustion. For biomass combustion plants, CFD modelling proved to be a highly efficient tool for process analyses as a basis to optimise plant design and control concerning the following issues:

- Improved air staging, temperature control and utilisation of the primary combustion zone in order to reduce NO_x emissions by primary measures.
- Efficient mixing of unburned flue gas with re-circulated flue gas and secondary air, better utilisation of the furnace and boiler volume in order to achieve an efficient flue gas burnout, a reduction of the furnace and boiler volume as well as a reduction of excess air.
- Reduction of local velocity and temperature peaks in order to reduce material stress, erosion and ash deposit formation.
- Sensitivity analyses concerning the influence of different fuels and operating conditions in order to supply a basis for an optimised plant control.

Summarising, CFD aided technology and plant development has the advantage that it leads to more compact combustion plants, considerably reduced pollutant emissions at enhanced plant efficiencies and increased availabilities due

to an adequate design of the furnace and boiler geometry. Moreover, CFD leads to a more reliable plant design as well as to reduced development times and costs. For the design of biomass combustion plants, CFD simulations are presently applied for:

- All size classes: small-, medium-, and large-scale systems
- Different biomass combustion technologies: wood log fired boilers and stoves, fixed bed and grate furnaces, spreader stoker furnaces, pulverised fuel furnaces and fluidised bed furnaces
- Different boiler types: fire tube boilers, water tube boilers and thermal-oil boilers
- Various biomass fuels: untreated woody biomass fuels like wood pellets, sawdust, wood chips, bark and wood logs, treated woody biomass fuels like waste wood and fibre boards as well as agricultural and herbaceous fuels like straw, olive residues and miscanthus.

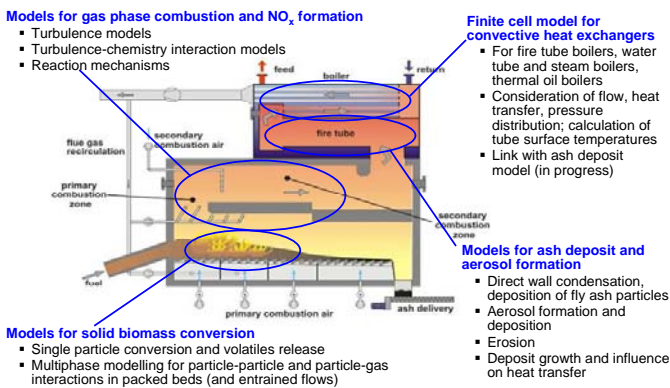


Figure 25: CFD simulation of biomass combustion plants – model overview

A review about state-of-the-art models for biomass combustion systems, new model approaches and of work performed in different research groups in Europe is provided by [32,33]. In the following, an overview about models for biomass combustion plants and their application is given. In Figure 25 the scheme of a biomass grate furnace with a fire tube boiler is shown in order to illustrate relevant processes in the plant and CFD modelling approaches.

Modelling of solid biomass conversion

In common engineering applications, the combustion of solid biomass on the grate is presently simulated by empirical 0D models or by 1D models. The empirical models serve to provide release profiles as boundary conditions for the following CFD simulation of gas phase but give no information about combustion on the grate and relevant influencing parameters. Also 1D models are not able to sufficiently describe the processes on the grate since mixing of the fuel particles with the grate bars in different grate systems and the combustion of thermally thick particles can not be captured. Therefore, research work in different groups is focussing on the development of layer models for thermally thick fuel particles and their link with 2D or 3D packed bed combustion models. In contradiction to packed beds, the combustion of solid biomass in pulverised fuel furnaces can be modelled sufficiently accurate with Lagrangian multiphase models, since the solid biomass combustion processes are of lower complexity [34]. When particles become thermally

thick, layer models can be applied and when the local volume fraction of particles is increasing (approximately > 10%), new multi-phase models accounting also for particle/particle interactions provide an improvement of prediction accuracy. Combustion of solid biomass in fluidised bed furnaces is highly complex and not fully understood so far. Therefore, no reliable CFD models for engineering purposes exist and simulations in fluidised bed furnaces are focussing only on the free board and down-stream sections.

Modelling of gas phase combustion and NO_x formation

For turbulent reactive flue gas flow in the combustion chamber several turbulence and gas phase combustion models exist. For gas phase combustion in biomass grate furnaces usually Eddy Dissipation Models with global 2-step, 3-step or 4-step reaction mechanisms are applied. CFD simulations are successfully applied to design and optimise furnace geometries including the nozzles for the injection of secondary air and re-circulated flue gas concerning improved furnace and boiler utilisation, turbulent mixing of flue gas with air, flue gas burnout and the reduction of excess air as well as concerning the reduction of velocity and temperature peaks in order to reduce material erosion and ash deposit formation.

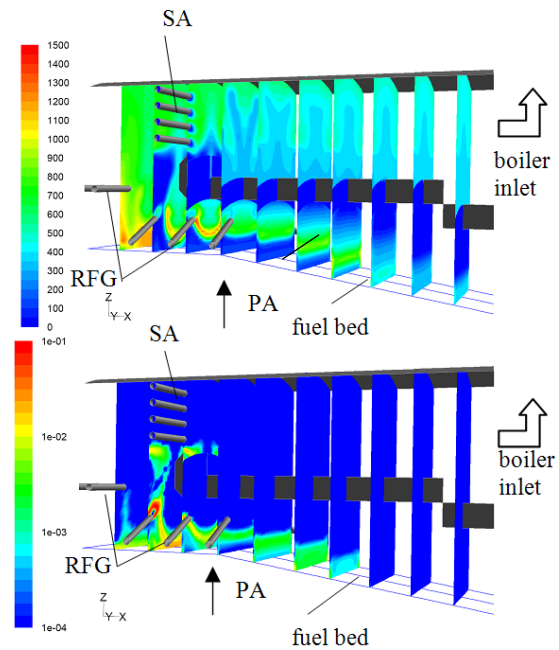


Figure 26: Profiles of NO (top) [ppmv] and net production rate of N₂ (bottom) [kg/m³] (indicator for NO_x reduction) in a biomass grate furnace

Explanations: nominal boiler load 440 kW_{th}; fuel fibre board, fuel nitrogen content 6.5 [wt.% d.b.]; model: Eddy Dissipation Concept / reduced reaction mechanism with 25 species and 104 reactions [37]; PA...primary air; SA...secondary air; RFG...re-circulated flue gas

However, with this simple combustion models it is not possible to simulate gas phase NO_x formation due to the high complexity of turbulence-chemistry interaction. However, there is a need for efficient design tools for low-NO_x furnaces, since the issue of NO_x emission reduction is gaining increasing importance due to continuously stricter emission limits and due to the combustion of new agricultural and herbaceous biomass fuels with high nitrogen contents. Increasing computer capacities allow for the implementation of more sophisticated gas phase combustion models in combination with detailed and reduced reaction mechanisms.

BIOS in co-operation with Graz University of Technology and the Austrian bioenergy competence centre Bioenergy 2020+ have implemented an advanced gas phase combustion model in combination with detailed and reduced reaction kinetics for the purpose of a more fundamental description of the combustion process and especially for the prediction of NO_x formation [35]. In order to define the release of the NO_x precursors during solid biomass combustion on the grate an empirical release model was extended by release profiles for the most relevant N-species NO , NH_3 and HCN [28,36]. Validation simulations showed that with this model all relevant trends concerning NO_x emissions in dependence of fuel nitrogen content, air staging, flue gas residence times and temperatures could be reproduced.

Figure 26 shows an example of NO profiles (top) and profiles of the net production rate of N_2 (bottom) in different vertical cross-sections of a biomass combustion plant. It is shown, that in the primary combustion zone the local net production rates of N_2 are positive, because under air lean conditions and at appropriate reaction temperatures, NO is reduced by the reaction with the NO_x precursors NH_3 and HCN . With this new model a simulation of the NO_x formation process in biomass grate furnaces is possible with reasonable accuracy at acceptable computation times for engineering applications. This model allows studying relevant influencing parameters on NO_x formation like fuel nitrogen content, air staging, flue gas temperatures and flue gas residence times in different plant zones as a basis for appropriate measures for an efficient NO_x reduction by primary and secondary measures.

Modelling of convective boiler sections and ash deposit and aerosol formation

In the last few years CFD modelling activities have been extended to the whole boiler including the convective section. Since in most cases the geometry of the tube bundles can not be resolved with a computational grid which can be handled by common computers, various CFD based heat exchanger models have been developed. At BIOS in co-operation with Graz University of Technology a porous zone based finite cell heat exchanger model describing flow and heat transfer as well as surface temperatures of the tubes for the most relevant boiler types (water tube boiler, thermo-oil boiler and fire tube boiler) has been developed. This model makes it possible to consider the furnace and boiler sections (including the secondary heat carrier, e.g. water) within simulations [32]. The results show that the CFD model gives considerably more detailed information than conventional 1D calculation methods especially in regions after deflections with high temperature gradients of the flue gas flow and that it can be applied as an efficient boiler design tool.

Ash related problems like aerosol and ash deposit formation as well as corrosion are of major relevance in biomass combustion plants especially when firing fuels with high ash content (e.g. waste wood, herbaceous and agricultural fuels). At Graz University of Technology in co-operation with BIOS and Bioenergy 2020+ a flexible and comprehensive ash deposit formation model is currently being developed in order to allow for a prediction of ash deposit formation in biomass combustion plants in dependence of fuel type and plant operation conditions [32,33,38]. With this model a world leading position could be achieved. At present, the model allows for the simulation of the time dependent ash deposit formation and the influence on

heat transfer in the furnace and the radiative section of the boiler under consideration of wall condensation of ash forming elements as well as the deposition of coarse fly ash particles. Figure 27 shows an example of the deposition mass fluxes of coarse fly ash particles (top) and ash vapours (bottom) in a pilot-scale grate furnace including the radiative section of a fire tube boiler. Generally the highest deposition mass fluxes occur in the furnace section due to high local impaction rates of fly ash particles as well as high surface and particle temperatures. The highest deposition rates by wall condensation occur in the water-cooled boiler section. They are comparably low at the beginning of plant operation but increase the stickiness of the boiler walls due to growing deposit thickness.

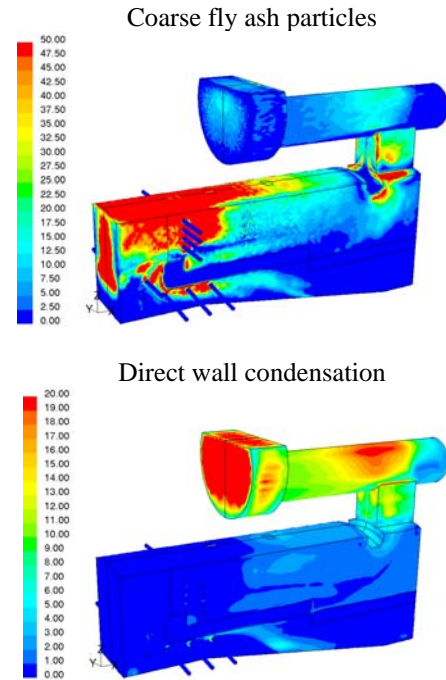


Figure 27: Deposition mass fluxes [$\text{mg}/\text{m}^2\text{s}$] to the walls of a biomass grate furnace and the flame tube of a fire tube boiler
Explanations: fuel: waste wood, nominal boiler load $440 \text{ kW}_{\text{th}}$; operation duration: 1 hour

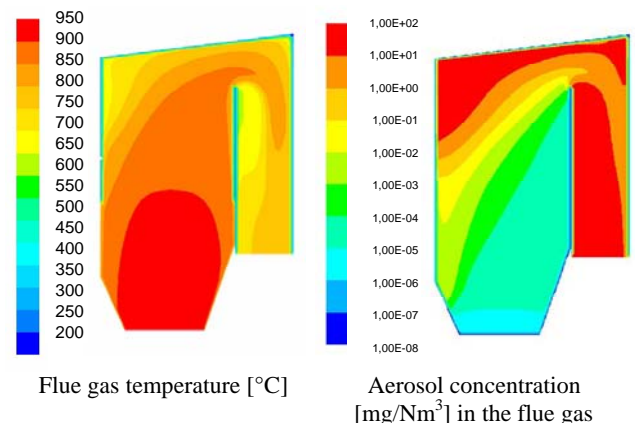


Figure 28: Aerosol concentrations (mg/Nm^3) in the flue gas and flue gas temperatures in the first and second radiative duct of a biomass fired steam boiler
Explanations: nominal boiler load: $40 \text{ MW}_{\text{th}}$

Moreover, the influence of aerosols formation, deposition and erosion is considered. In Figure 28 results concerning modelled aerosol concentrations and flue gas temperatures in the first and second radiative boiler section of a biomass fired

steam boiler are depicted. Aerosols are formed when flue gas temperatures decrease below the saturation point of the ash forming vapours.

An enhancement and further tests of the model are ongoing. Especially important is the link of the deposit formation model with the convective heat exchanger model in order to allow for a simulation of ash deposit formation in the whole plant including the convective boiler section [39]. Concluding, a powerful tool for an efficient design of biomass furnaces and boilers is under development. With such a model the influence of the fuel fired and operation conditions on the deposit formation processes can be investigated already in the design phase of a plant allowing for appropriate measures in order to reduce ash deposit formation. Even at the present state of development, the model can be applied for the support of plant designs by providing qualitative information.

INTELLIGENT PROCESS CONTROL SYSTEMS

State-of-the-art control systems for biomass combustion plants usually work with 4 control circuits which control the load, the furnace temperatures, the pressure in the furnace, and the secondary air ratio. Each of these control circuits is responsible to set respective output parameters based on measured data and defined setpoints. They are to a large extent independent from each other. Dependencies and sometimes highly nonlinear interrelations between the different output parameters are not or only to a small extent taken into consideration. Consequently, conventional control systems work sufficiently efficient at steady state but not efficient in intermediate conditions (e.g. load changes or changes of the fuel quality). The potential of a modern biomass furnace which has an optimised furnace geometry and nozzle design is not fully utilised concerning low emission operation and high energetic efficiencies by conventional control systems.

Within recent years control systems implementing neuronal networks, fuzzy logic, and model based control gained more and more importance but are at the moment not or only to a small extent applied for biomass combustion plants.

With neuronal networks it is possible to develop a mathematical model in a fast and convenient way directly from experimental data. The major drawback of neuronal networks is the fact that the models are not based on the underlying physical relations and are only valid within the scope of the experimental data provided. Consequently, validity is not guaranteed for every state.

Fuzzy control is based on a description of a system based on fuzzy logic, which allows to deduce a mathematical model from a linguistic description of the system behaviour. Hence fuzzy control has the advantage that the operator's expertise can be used to develop a control strategy very quickly. The disadvantage of fuzzy concepts is the fact that states which are not considered by rules can lead to malfunctions and that there is no deterministic procedure for the design of a fuzzy controller. Consequently, liberties in the realisation of fuzzy controllers can degrade the results significantly. Up to now, fuzzy concepts are partly implemented in control systems for biomass combustion plants but there is no control system available which is completely based on fuzzy logic.

Model based concepts require a preferably simple mathematical model that describes the main interrelations of the physical system to be controlled [40,41,42]. Based on this

mathematical model it is possible to develop a controller which takes the nonlinearity and the coupling of the different process variables explicitly into account, wherefore a well established theory is available. Consequently, the so designed model based controller is able to react more efficiently on unsteady operating conditions than the currently in combustion plants used control systems. The only disadvantage of the described model based control strategies is that they are very labour intensive in the case that no applicable mathematical model is available. If such models are available, then model based systems are evaluated to be the most suitable and efficient solution.

It is expected that new control concepts especially model based control strategies and fuzzy control will gain more importance for biomass combustion systems in the near future.

SUMMARY, CONCLUSIONS AND OUTLOOK

Together with hydropower, biomass is the most important renewable energy source in the European Union. In the field of energetic utilisation of solid biomass, combustion is the most advanced and market-proven application. Consequently, the energetic use of solid biomass is primarily based on biomass combustion at presence. Biomass combustion technologies, like fixed-bed, fluidised bed and pulverised fuel combustion, are currently available for different types of biomass fuels covering a wide range of plant capacities. Concerning plant size, the different applications of biomass combustion can be divided into small-scale biomass combustion systems (capacity range: <100 kW_{th}), medium-scale combustion systems (capacity: range: 100 kW_{th} to 20 MW_{th}), large-scale combustion systems (capacity: range: >20 MW_{th}), and co-firing of biomass in coal fired power stations (capacity range: usually some 100 MW_{th}).

Regarding plant design, chemical and physical properties of biomass fuels are of great importance. The fuel properties affect fuel transport, storage and feeding systems as well as the grate, furnace and boiler technology. Especially ash related problems like aerosol formation, slagging, deposit formation and corrosion in biomass combustion processes are always strongly associated with the fuel chemistry, in detail, with the concentration and speciation of inorganic compounds in the fuel. Important guiding parameter are, in this respect, the molar ratios (K+Na)/(2S+Cl), 2S/Cl and the sum of K, Na, Zn and Pb in the fuel. High molar ratios of (K+Na)/(2S+Cl) indicate lower HCl and SO_x emissions. The molar ratio of 2S/Cl indicates the preferred formation of alkaline sulphates or alkaline chlorides. K, Na, Zn and Pb are the most relevant aerosol forming elements. With increasing concentrations of these elements the probability of aerosol formation as well as deposit formation increase as well. Consequently, if an ash related problem has to be evaluated always comprehensive knowledge about the fuel is needed.

NO_x emissions from biomass combustion applications are mainly a result of complete oxidation of fuel nitrogen, whereas NO_x formed from nitrogen in the air is usually of minor relevance in most biomass combustion applications due to moderate combustion temperatures. NO_x emissions from biomass combustion can be efficiently reduced by primary measures or combinations of primary and secondary measures. In addition, NO_x modelling is of great relevance for an improved future plant design.

For biomass combustion plants, CFD modelling proved to be a highly efficient tool for process analyses as a basis to

optimise plant design and control concerning improved air staging, temperature control and utilisation of the primary combustion zone in order to reduce NO_x emissions by primary measures, efficient mixing of unburned flue gas and reduction of local velocity and temperature peaks in order to reduce material stress, erosion and ash deposit formation. Consequently, CFD aided technology and plant development has the advantage that it leads to better utilisation of combustion plants, considerably reduced pollutant emissions at enhanced plant efficiencies and increased availabilities due to an adequate design of the furnace and boiler geometry.

On-going research mainly focuses on the utilisation of new biomass fuels (annual crops, short rotation plants, waste materials from the agricultural and the food industry, etc) as well as the further development of combustion technology towards next generation (“zero emissions”) systems. The main focus regarding emission reduction is on aerosol emissions as well as on NO_x reduction. Concerning CHP systems new developments focus on advanced and highly efficient systems. In this respect increased steam parameters and higher availability are important targets. Regarding process control strategies for combustion plants, new concepts like model based systems will gain more and more importance. Future modelling activities aim at CFD models to simulate the whole biomass combustion plant (“virtual biomass combustion plant) interlinking solid fuel combustion, gas phase reactions, the boiler as well as emissions and ash related problems.

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