Promoting the penetration of agrobiomass in European rural areas

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D4.5 Best practice guidelines for agrobiomass combustion in heating plants

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Deliverable Factsheet

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Abbreviations

d.b.	Dry basis
GCV	Gross calorific value
MCP	Medium combustion plant
NCV	Net calorific value
WP	Work package
w.b.	Wet basis
CO	Carbon monoxide
OGC	Organic gaseous compounds
NOx	Nitrogen oxides ($NO+NO_2$, usually expressed as NO_2)
PM	Particulate matter

Project consortium

#	Full name	Acronym
1	Ethniko Kentro Erevnas kai Technologikis Anaptyxis	CERTH
2	Fundación Centro de Investigación de Recursos y Consumos Energéticos	CIRCE
3	Asociación Española de la Valorización Energética de la Biomasa	AVEBIOM
4	BIOS BIOENERGIESYSTEME GmbH	BIOS
5	Food & Bio Cluster Denmark	FBCD
6	Bioenergy Europe	B.E.
7	Zelena energetska zadruga za usluge	ZEZ
8	Asociatia Green Energy	GEA
9	Institouto Agrotikis kai Synetairistikis Oikonomias INASO-PASEGES	INASO-PASEGES
10	Bioenergy Association of Ukraine	UABIO
11	White Research Sprl	W.R.
12	Agronergy	AGRONERGY
13	Association d'Initiatives Locales pour l'Energie et l'Environnement	AILE

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Executive Summary

Within Work Package 4 of the AgroBioHeat project comprehensive information regarding the present state of agrobiomass utilisation in small (residential) and medium-scale heating plants has been gathered. Therefore, the following actions have been performed:

- Evaluation of the technological state-of-the-art of agrobiomass combustion systems based on interviews with manufacturers of heating plants and flue gas cleaning systems.
- Performance of test stand testing campaigns with commercially available small-scale (residential) heating boilers to investigate their performance and emissions when utilising different agrobiomass assortments.
- Performance of field tests at operating heating plants utilising different agrobiomass assortments.

Based on the know-how and experience available at partner BIOS on biomass combustion processes in general and on the results and experiences gained from the work within work package 4, best practise guidelines regarding agrobiomass combustion in heating plants have been worked out which are summarised in this report.

Within Deliverable Report 4.2, *Agrobiomass fuels and utilization systems*, heating systems which are applicable for agrobiomass utilisation as well as their single components have already been described in detail. Consequently, Deliverable Report 4.2 forms a basis for this report. The guidelines presented in this report at first highlight the impact of specific fuel properties of agrobiomass on the combustion process and then summarise relevant aspects regarding the suitability of combustion plant technologies for utilisation of agrobiomass. These guidelines shall support installers, ESCOs (Energy Service Companies), future operators of heating plants and people who are interested to initiate an agrobiomass heating project, when selecting appropriate plant technologies and highlight aspects which should be considered when comparing different combustion systems with respect to agrobiomass utilisation.

Introduction

Within Task 4.1, *Technological state-of-the-art and trends*, 48 manufacturers of biomass boilers and flue gas cleaning devices have been contacted by the consortium and have been asked to fill in a questionnaire regarding their technologies which may be suitable for agrobiomass combustion as well as their opinions regarding the status and the future trends regarding agrobiomass heating in Europe. Within Task 4.2, *Operational compliance for Ecodesign*, six small-scale (residential) biomass boiler systems, partly equipped with electrostatic precipitations for flue gas cleaning, have been tested at lab test stands with a broad range of different agrobiomass assortments. Moreover, within Task 4.3, *Operational compliance in operating facilities*, test runs with accompanying measurements, sampling and analyses at heating plants operated with agrobiomass have been performed. From Task T4.1, *Technological state-of-the-art and trends*, already a comprehensive report on *Agrobiomass fuels and utilization systems*, in which plant technologies available for agrobiomass combustion are described, resulted.

Based on the data and experiences gained from these three Tasks as well as on the expertise regarding biomass combustion plant design and operation available at partner BIOS, *Best practice guidelines for agrobiomass combustion*, should be generated within Task 4.4 of the AgroBioHeat project.

The target group for these guidelines should be installers, ESCOs (Energy Service Companies) and future operators of agrobiomass-based heating plants. The guidelines should support them in identifying suitable technologies (combustion and flue gas cleaning devices) for their specific demands in terms of heat production, capacity range, spectrum of agrobiomass fuels available and emission limits to be kept. Additionally, the guidelines should provide information regarding specific maintenance related issues such as ash related problems, boiler cleaning as well as measures to avoid corrosion risks.

The scope of the AgroBioHeat project covers small-scale (residential) and decentralized medium-scale heating systems, thus reaching from a capacity range of some kW up to about 1 MW. In this capacity range it has generally to be distinguished between two types of heating plants:

- Heating systems with a rated heat output up to 500 kW, which are regulated, when fired with wood fuels, under the EU Ecodesign Regulation (2015/1185). Such boilers are usually manufactured in serial production and have to pass type testing before being introduced into the market.
- Heating systems with a rated heat output of more than 500 kW. Usually these systems are designed according to the demands of the specific client. Compliance with specific emission limit values must be demonstrated during commissioning. In contrast with systems below 500 kW, no EU-wide emission limits resp. regulations exist for the capacity range between 500 kW and 1 MW and therefore, national legislation has to be applied. For plants between 1 MW and 5 MW fuel power the EU Medium Combustion Plant (MCP) Directive (2015/2193) applies.

Since the small-scale (residential) systems are produced in serial production and are designed for application by private persons while the larger systems (> 500 kW) are usually purpose built and consider client specific demands, the systems are discussed separately in these guidelines.

1. Impact of fuel quality on the combustion process

1.1. Biomass fuel standards

Fuel standards are an important instrument to describe biomass fuels and to define binding quality criteria regarding relevant fuel properties. EN ISO 17255 therefore characterizes different biomass fuels, however, there is a strong focus on woody biomass (wood chips, wood pellets, logwood). Regarding agrobiomass, only non-wood pellets are explicitly considered in EN ISO 17255-part 6. Therefore, for agricultural biomass fuels such as straw, miscanthus, prunings, stones and shells no appropriate European standards which define quality classes exist. However, in Spain there are specific standards for olive stones and some types of fruit shells, UNE 164003:2014 "*Solid biofuels. Fuel specifications and classes. Graded olive stones*" and UNE 164004:2014 "*Solid biofuels. Fuel specifications and classes. Graded fruit shells*". Class types A1, A2 and B are established in both standards.

Due to this lack for standardization, a broad range of fuel qualities and biomass fuel compositions has to be considered when utilizing agrobiomass. Therefore, in this section a brief overview over combustion related problems which are associated to certain relevant fuel parameters is provided.

1.2. Relevant parameters influencing the combustion-related properties of biomass fuels

The chemical composition of biomass fuels can vary concerning the concentrations of the main elements (C, H, O, N), sulphur (S) and chlorine (Cl) as well as of the ash content respectively the concentrations of ash forming elements. Thereby, regarding N, S, Cl and ash forming elements agrobiomass shows by far wider composition ranges compared with wood fuels. In the following the impacts of the most relevant parameters on furnace and boiler operation are briefly summarized.

Typical ranges for relevant parameters of different in terms of thermal utilization interesting agrobiomass assortments such as miscanthus, nut shells, olive stones, prunings, SRC, straw and sunflower husks are listed in the **Agrobiomass Factsheets**, which can be downloaded from the AgroBioHeat project webpage (https://agrobioheat.eu/agrobiomass-factsheets/). Moreover, they are contained in *Deliverable Report D4.1, Agrobiomass fuels and utilization systems.*

In Table 1 some relevant fuel properties of these agrobiomass assortments are listed and compared with database values for chemically untreated wood chips and wood pellets from the BIOS-internal biomass fuel database. Class A1 wood pellets and chemically untreated wood chips are used as reference since they are the most common fuels applied in heating systems in the capacity range up to 1 MW all over Europe.

Table 1. Typical compositions of selected agrobiomass assortments and comparison with database values for chemically untreated wood chips and class A1 wood pellets

Property	Unit	Wheat straw	Olive tree pruning hog fuel	Vineyard pruning pellets	Olive stones	Almond shells	Sunflower husk pellets	Miscanthus (chopped)	Willow & Poplar (chipped)	Wood chips	Pellets (EN17225 class A1)
Moisture, M	wt% w.b.	15	27	10	15	11	10	15	20 - 50	20 - 50	6 – 8
Ash, A	wt% d.b.	5.0	4.2	4.5	1.2	1.6	4.0	4.0	2.0	0.24 - 1.21	0.28 - 0.7
Net Calorific Value, NCV	MJ/kg w.b.	14.6	12.9	15.7	15.8	16.1	15.7	14.7	8.0	8.1	16.9 - 18.8
Bulk Density, BD (loose)	kg/m³ w.b.	60	230	710	730	410	550	130	250	175 - 230	600 - 750
Bulk Density, BD (bales)	kg/m³ w.b.	100									
Energy Density (loose)	MWh/m³	0.24	0.83	3.10	3.20	1.83	2.40	0.53	0.56	0.79 - 1.04	2.8 - 3.9
Energy Density (bales)	MWh/m³	0.41									
Nitrogen, N	wt% d.b.	0.5	0.93	0.81	0.3	0.4	0.8	0.7	0.5	0.08 - 0.23	0.06 - 0.21
Sulphur, S	wt% d.b.	0.1	0.08	0.07	0.02	0.01	0.1	0.2	0.04	0.004 - 0.022	< 0.015
Chlorine, Cl	wt% d.b.	0.4	0.04	0.02	0.1	0.02	0.06	0.2	0.02	0.0008 - 0.0128	< 0.006
Calcium, Ca	mg/kg d.b.	4,000	9,000	10,000	1,300	1,300	5,000	2,000	5,000	590 - 5,000	670 - 1,700
Potassium, K	mg/kg d.b.	10,000	5,600	5,400	2,300	4,600	11,000	7,000	2,500	240 - 1,700	370 - 680
Sodium, Na	mg/kg d.b.	500	460	170	600	2,500	50	70	25	2 - 150	11 - 90
Silica, Si	mg/kg d.b.	10,000	2,100	2,800	900	630	600	8,000	500	70 - 1,760	100 - 800

w.b.: wet basis, d.b.: dry base; data sources: see Deliverable Report D4.2

1.2.1. Gross calorific value (GCV) and net calorific value (NCV)

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.

The gross calorific values of typical agrobiomass assortments are in a range which is comparable with the one of wood pellets and wood chips. Since agrobiomass assortments typically show low moisture contents (<30 wt% w.b.), their NCV exceeds in many cases the NCV of typical wood chip assortments with moisture contents between 20 and 50 wt% w.b. but is below the range of wood pellets.

1.2.2. Bulk density and energy density

Bulk density and especially the energy density (=bulk density * NCV/3600) of the fuel have to be considered with respect to

- fuel transport,
- storage, and
- fuel feeding systems.

In this respect pelletized biomass fuels show clear advantages compared to non-densified materials due to their higher bulk and energy density.

Loose agrobiomass assortments can show significantly deviating bulk densities starting with 60 kg/m³ for chopped straw up to about 730 kg/m³ for olive stones. Especially for low-density fuels, densification (baling of straw, pelletising of e.g. sunflower husks) significantly enhances the bulk density and thereby also the energy density and thus lowers costs for transportation and storage.

1.2.3. Nitrogen (N) content

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 (see Figure 1).

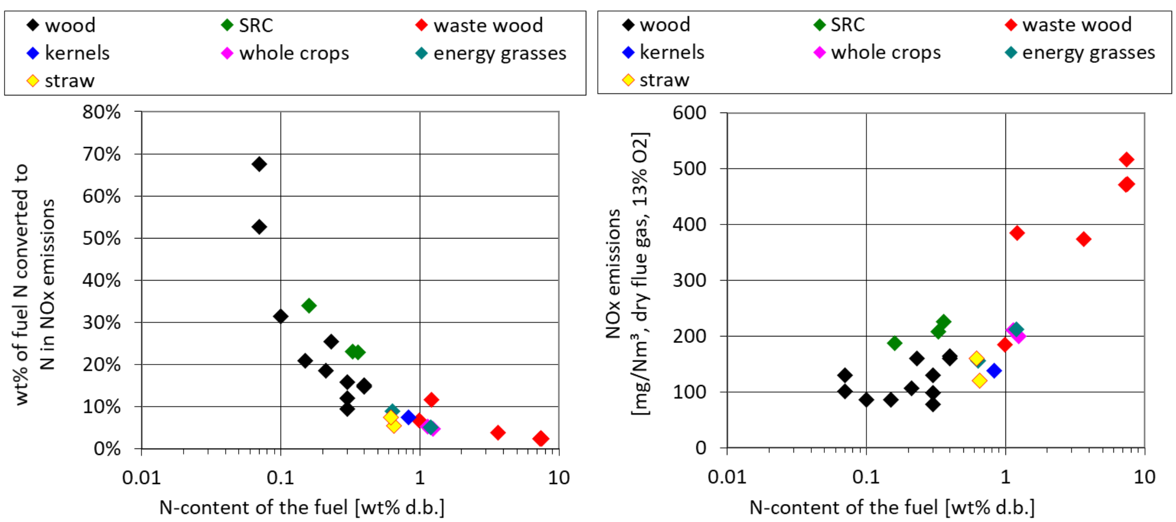

Figure 1: NO_x emissions (right) and N conversion (left) related to the N content of the fuel
Results from test runs at real-scale plants equipped with air staging; NO_x calculated as NO_2;
source: OBERNBERGER I., 2014: Strategy for the Application of Novel Characterization Methods for Biomass Fuels: Case Study of Straw. In: Energy Fuels 2014, 28, 1041–1052

Compared to chemically untreated wood chips and class-A1 wood pellets all agrobiomass fuels mentioned in Table 1 show higher N contents and consequently, higher NO_x emissions compared to wood result from the combustion of these fuels.

1.2.4. Sulphur (S) and chlorine (Cl) content

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.

In Figure 2 results of test runs performed within the AgroBioHeat project with two small-scale boilers and different agrobiomass assortments are presented, which clearly show that with increasing S and Cl contents in the fuel, the SO_x and HCl emissions increase.

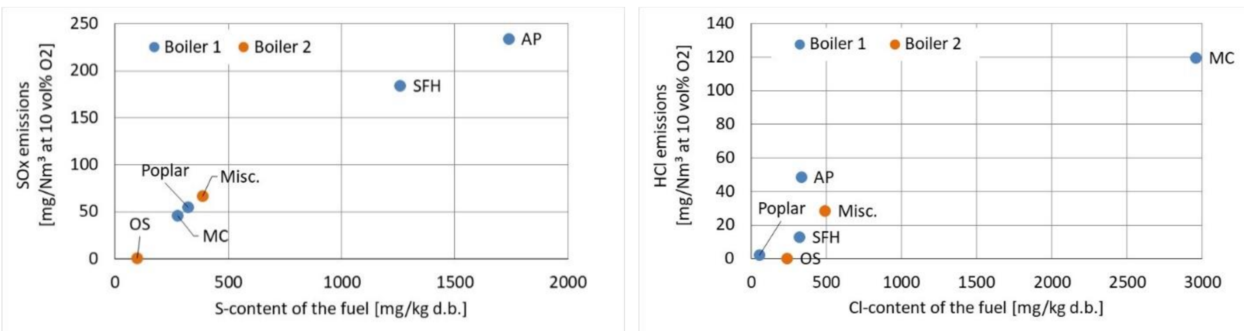

Figure 2: SO_2 and HCl emissions downstream boiler vs. S and Cl content of the fuel applied
Explanations: results of test runs at two different small-scale boilers within the AgroBioHeat project; mean values of three measurements performed during each test run; d.b. dry basis; SO_x expressed as SO_2; SFH: sunflower husk pellets; AP: agropellets; MC: maize cobs; OS: olive stones; Misc: miscanthus.

Ash deposits are mainly formed by alkali metal salts such as K_2SO_4 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, significant impact of the S- and Cl-contents on high-temperature corrosion of heat exchanger surfaces (mainly relevant for superheaters in steam boilers where it limits the steam temperatures that can be achieved) is given.

Furthermore, it has to be taken into account, that increasing S and Cl concentrations in the flue gas also show impacts on low-temperature corrosion in boilers, economizers, filters and air pre-heaters, either by acid dew point corrosion or by formation of corrosive hygroscopic salts. With respect to plants in the target capacity size of these guidelines (up to about 1 MW), this aspect is of higher relevance since in such plants usually hot water boilers with comparably low boiler surface temperatures and no steam boilers are applied.

Compared with chemically untreated wood fuels, many agrobiomass assortments show elevated S and Cl contents and consequently, higher SO_x and HCl emissions result. Moreover, high-temperature and low-temperature corrosion related issues have to be considered during boiler and plant design.

1.2.5. Ash content

Besides its influence on the GCV, the **ash content** has to be considered concerning

- the de-ashing system,
- ash storage,
- ash utilisation,
- the grate design as well as
- particulate matter emissions

Therefore, the ash content is an important parameter to be considered during plant design. It has to be pointed out that most agrobiomass assortments show in comparison with wood fuels elevated ash contents. Especially the comparably high ash contents of prunings, straw, miscanthus and sunflower husk pellets (see Table 1) may lead to combustion related problems.

1.2.6. Contents of relevant ash forming elements and their influence on ash formation

For most agrobiomass fuels, ash formation processes and ash related problems are of major relevance. For a better understanding of the terminology applied in these guidelines, 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 categorized 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.

The **ash melting behaviour** of grate ashes is an important issue to be considered when utilizing agrobiomass. In general, ash melting and slag formation in biomass combustion systems 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. However, as shown in Table 1, for most agrobiomass assortments high K and Si contents as well as comparably low Ca, Mg and K contents prevail which lead to ash melting temperatures which are typically below those of chemically untreated wood assortments. Consequently, a higher risk regarding slag formation on the grate, which may disturb the combustion process and may cause problems during de-ashing is given for agrobiomass combustion.
To assess risks regarding ash melting and slagging the so-called ash melting index can be applied. This index is calculated as the molar ratio of (K+Si+P)/(Ca+Mg+Al) and therefore considers the most relevant elements which increase or decrease ash melting temperatures. Low index values (around 1 and below, as they are typical for chemically untreated wood fuels) indicate a low risk for ash melting while with increasing value of the index ash melting temperatures decrease (see Figure 3). Based on the evaluation of the ash melting

index wheat straw and Miscanthus (typical values between 5 and 7) have for instance to be assessed as critical assortments regarding slagging tendencies.

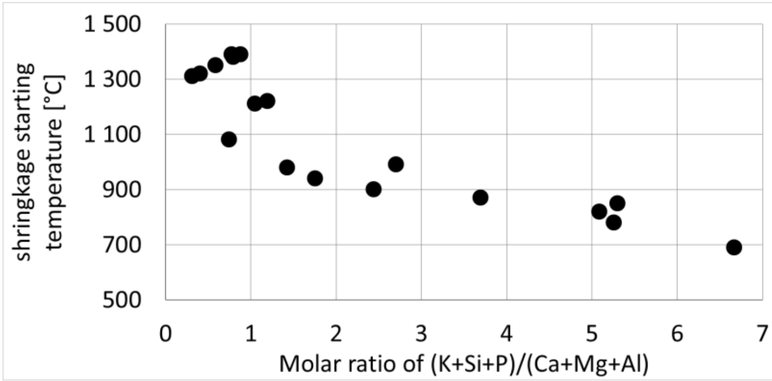

Figure 3: Relation of the fuel index (K+Si+P)/(Ca+Mg+Al) with the ash melting temperature
source: OBERNBERGER I., 2014: Strategy for the Application of Novel Characterization Methods for Biomass Fuels: Case Study of Straw. In: Energy Fuels 2014, 28, 1041–1052

> Agrobiomass assortments can show, depending on their composition regarding ash forming elements, a broad variation range concerning ash melting temperatures with straw as the most problematic fuel. Therefore, knowledge about the ash melting properties is essential for the implementation of appropriate measures in boiler design to overcome slagging problems. As a first indication the fuel index molar ratio of (K+Si+P)/(Ca+Mg+Al) can be used to assess slagging tendencies of a specific fuel.

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 µm. 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). Besides its contribution to particulate emissions, coarse fly ashes are also relevant regarding the formation of deposits in the boiler and in the furnace. Especially when utilizing fuels with low ash melting temperatures, formation of very hard ash deposits on furnace walls may occur, which can only be manually removed during maintenance shut-downs.

Fine particulate matter (particles smaller than 1 µm – PM_1) 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 downstream the boiler and upstream any particle precipitation device on the K, Na, Zn and Pb content in the fuel.

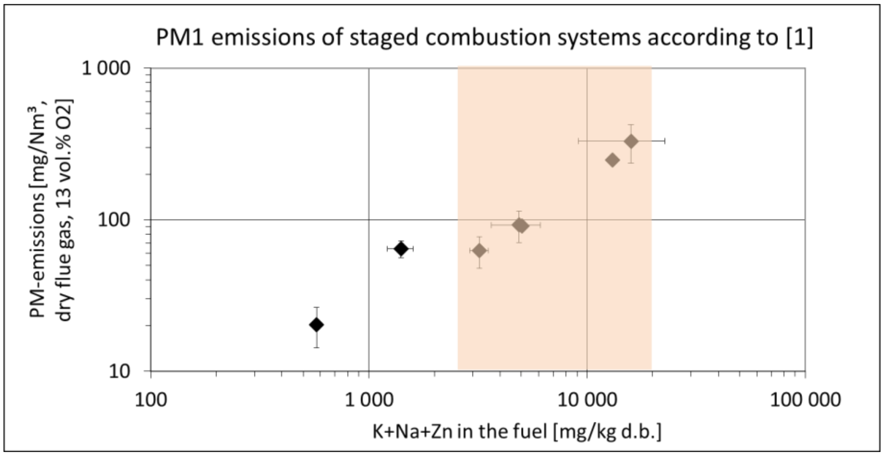

Figure 4: PM_1 emissions as a function of the concentration of aerosol-forming species (K + Na + Zn + Pb) in the fuel Composition range of typical agrobiomass assortments highlighted
[1] OBERNBERGER I., 2014: Strategy for the Application of Novel Characterization Methods for Biomass Fuels: Case Study of Straw. In: Energy Fuels 2014, 28, 1041−1052

When considering the typical K and Na contents of agrobiomass assortments (see Table 1), comparably high fine particulate matter emissions must be expected from most assortments. Filter systems or extreme air staging technologies are therefore needed to keep the particulate matter emissions low.

2. Guidelines for small-scale agrobiomass boilers

2.1. Introduction

In this respect, small-scale means residential biomass boilers with a capacity range <500 kW. In case of wood combustion, the EC Regulation 2015/1189 establishes Ecodesign requirements for placing such boilers on the market and putting them into service. However, this regulation presently does not cover non-wood fuels.

The highest sales numbers for small-scale residential boilers for wood chips and wood pellets are in the capacity range below 50 kW which is due to the fact that they are usually applied for space heat and domestic hot water production in single house or larger residential or public buildings. Accordingly, private use dominates, which also defines the requirements for these systems from a user point of view.

- They should work without the need of a permanent observation.
- Maintenance work should be at a minimum.
- Operation comfort for the user must be high.
- The systems must be robust to achieve a maximum availability.
- Fuel storage capacities are restricted and fuel deliveries per year should be reduced to a minimum

From an efficiency and emission point of view, the limit values according to the Ecodesign regulation respectively the national regulations must be kept. However, since non-wood fuels are presently not covered by Ecodesign, the Ecodesign requirements for wood fuels shall be the basis for the following discussions regarding agrobiomass combustion in such systems. In this respect it has to be pointed out that test stand tests performed within the AgroBioHeat project confirmed that there are residential-scale boiler technologies available on the market which can keep these requirements and the related emission limits regarding the parameters CO, OGC and dust. NO_x emissions are typically higher than the Ecodesign emission limit value for wood fuels but this is due to the elevated N contents of agrobiomass and not due to the combustion technology applied.

In the following the most relevant aspects to be considered when evaluating a residential-scale combustion system with respect to agrobiomass utilisation are discussed.

2.2. Fuel storage and fuel feeding system

In residential heating systems storage space is usually limited. Moreover, in terms of user comfort, the number of fuel deliveries per year should also be minimized. Thus, a high energy density of the fuel is of great advantage which favors agrobiomass assortments like olive stones or densified (pelletised) agrobiomass over loose chipped or chopped fuels.

Moreover, the energy density and the particle size of the biomass fuel are the most relevant parameters regarding the design of the fuel feeding system. Experience from the test runs performed within

AgroBioHeat revealed that when utilising olive stones or 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.

2.3. Grate concept and de-ashing of the grate

Most agrobiomass assortments are characterised by significantly higher ash contents than wood pellets or wood chips. Therefore, the grate system and especially the de-ashing of the grate play a major role in combustion technology design. The test runs performed within AgroBioHeat clearly indicated that moving grate systems are much more suitable for agrobiomass combustion than fixed grates and top-fed retort burners.

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 grate (geometry of the opening from the fuel feeding system to the grate) is needed.

Due to the usually higher ash content an ash layer quickly forms on the grate which has to be continuously removed. This aspect also favours moving grate systems with continuous de-ashing. Movements of the grate elements thereby can support the breaking of sintered ash agglomerates in case of utilisation of agrobiomass assortments with low ash melting temperatures (e.g. straw or miscanthus pellets). 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.

The measures mentioned above 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.

Regarding the utilisation of pelletised fuels with high ash contents it has to be considered that they 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 within AgroBioHeat 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: Pictures of ashes on the grate (left) and after de-ashing with a screw (right) during wheat straw combustion

2.4. Application of advanced air staging concepts

Ash melting on the grate is one of the most relevant problems when utilising agrobiomass fuels. The application of an appropriate air staging concept is one basis to achieve low gaseous and particulate emissions. However, it is also an appropriate measure to keep the fuel bed temperatures low and to reduce respectively avoid slagging problems.

2.4.1. 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 and shall be equipped with separate combustion air supplies in order to create a dedicated zone with reducing atmosphere in the primary combustion zone, which is also a relevant pre-requisite for NO_x reduction by primary measures and an oxidising atmosphere in the secondary combustion zone.

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.

2.4.2. Air staging concept

Air staging means that the primary air ratio respectively the air ratio in the fuel bed (on the grate) 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 (coarse fly ash emissions).

An additional option to better control the temperatures in the fuel bed is the application of flue gas recirculation into the primary combustion zone. Thereby, the recirculated flue gas reduces the oxygen content of the mixture of recirculated flue gas and primary air which enters the fuel bed and thereby reduces the fuel bed temperatures. However, flue gas recirculation below the grate is only used very rarely in residential-scale biomass boilers since it enhances boiler complexity.

At a given total excess air ratio (λ_{total}) of about 1.6 – 1.8 (typical values that have been achieved during test runs within AgroBioHeat), 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 (low CO and OGC emissions). To achieve low CO and OGC emissions also during partial load it is essential that also in this operation scenario low primary air ratios and thus appropriately high secondary air injection can be maintained.

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 air staging concept.

2.4.3. The special case of extremely staged combustion systems

Extremely staged combustion systems have been established on the wood chip and pellet boiler market. With such systems, the fuel is first gasified in a fuel bed (at a ratio λ between 0.2 and 0.3) which is significantly higher than the one of conventional grate-fired units[1]. The gases evolving from the fuel bed are then combusted in a gas burner, positioned directly above the fuel bed, with secondary air. With this concept almost zero CO and OGC emissions can be achieved. Moreover, due to the specific temperature profile of the high fuel bed as well as the low velocities of the gases in the flue gas, the dust emissions of these systems are very low. For wood fuels they reach values as low as 1 mg/Nm³ (at 13 vol% O_2). As test runs within AgroBioHeat have shown, these systems can also keep the dust emissions limits defined in the Ecodesign regulation for wood fuels when utilizing agrobiomass without the need for an electrostatic precipitator[2].

[1] OBERNBERGER I., THEK G., BRUNNER T., NOWAK P., MANDL C., KERSCHBAUM M., BORJABAD E., MEDIAVILLA I., PEÑA D., CARRASCO J., 2018: Next Generation Fuel Flexible Residential Biomass Heating Based on an Extreme Air Staging Technology with Ultra-low Emissions (plenary lecture). In: Proceedings of the 26th European Biomass Conference and Exhibition, May 2018, Copenhagen, Denmark, ISBN 978-88-89407-18-9, ISSN 2282-5819, pp. 7-15, ETA-Florence Renewable Energies (Ed.), Florence, Italy

[2] BRUNNER T., NOWAK P., MANDL C., OBERNBERGER I., 2021: Assessment of Agrobiomass Combustion in State-of-the-Art Residential Boilers. In: Proceedings of the 29th European Biomass Conference and Exhibition, April 2021, Marseille, Online, France, ISBN 978-88-89407-21-9, pp. 379-388

2.5. 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 thereby is 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.

Most of the false air sources mentioned above lead to an increased effective primary air ratio since the false air partly or fully flows through the fuel bed. Especially during partial load operation this can lead to decreased respectively too low secondary air volume flows and consequently a bad mixing of the secondary air with flue gases due to a reduced momentum of the secondary air. From such operation scenarios elevated CO and OGC emissions as well as increased soot formation may result.

2.6. 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). 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°C) must be long enough. Therefore, it is recommended to also insulate the first part of the secondary combustion chamber.

2.7. Boiler design and boiler cleaning

Since the application of agrobiomass is often 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 Cl 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. It is therefore 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.

2.8. Secondary measures regarding emission control

Due to the elevated ash and especially K contents of most agrobiomass 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 µm) 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, the ESP should be equipped with an automated cleaning system for the spraying electrode and the precipitation surfaces. These systems should be operated more frequently than during combustion of wood fuels in order to prevent for a loss of precipitation efficiency due to the formation of isolating dust layers on the ESP surfaces.

2.9. 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 of great advantage if the primary and secondary combustion air flows 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.

Excess air ratio control (λ probes) is state-of-the-art and should be applied for optimisation of the combustion control. The load control however should facilitate a low emissions operation as well as high efficiencies over the whole boiler load range. For wood fuels this is already state-of-the-art since within the Ecodesign regulation the operation at partial load has a dominant impact on the calculation of the so-called seasonal emissions and efficiencies, for which the respective emission limit values are defined. Therefore, also for the specific characteristics of agrobiomass fuels appropriate control systems should be implemented.

An advanced solution for combustion control is the so-called CO-λ-control. With this control concept, which applies sensors which measure the contents of oxygen and of unburned species in the flue gas (CO and hydrocarbons), the air supply can be permanently adjusted to achieve minimum CO and OGC emissions at a minimum excess air ratio. The control system automatically adapts to changing load conditions and varying fuel qualities.

Especially for small-scale boilers with water cooled furnace walls, soot formation may cause increased particulate matter emissions during partial load operation, and thus an appropriate adjustment of the excess air ratio (λ) is needed to not only reduce CO emissions but also to minimise soot formation.

3. Guidelines for medium-scale agrobiomass boilers

3.1.Introduction

In this respect, medium-scale means biomass boilers with a capacity range between 500 kW and 1 MW. It has to be emphasized that in the EU medium combustion plant directive (MCP) emission limit values for plants with capacities between 1 MW and 50 MW are defined, while for the capacity range between 500 kW and 1 MW no EU-wide regulations exist, thus national legislations have to be applied. This is of relevance since decentralized agrobiomass utilization, as it is the scope of the AgroBioHeat project, often is realised in the capacity range between 500 kW and 1 MW. However, in these guidelines we focus on operational issues and therefore, the lack for an EU-wide regulation regarding emission limits in this capacity range is of minor relevance.

One relevant difference compared with small-scale plants is that medium-scale combustion plants are typically not mass produced but designed under consideration of specific demands of the respective clients. This mainly applies to the selection of components for fuel storage and fuel feeding system, the selection and design of flue gas cleaning devices (e.g. cyclones, filters) and the geometric alignment of the different plant components within the overall plant concept.

In general, considering the broad variation range of the ash contents of agrobiomass fuels and the target capacity range of between 500 kW and some 1 MW, the application of moving grate fired combustion systems is recommended.

In the following the most relevant aspects to be considered when evaluating a medium-scale combustion systems with respect to agrobiomass utilization are discussed.

3.2. Harvesting and fuel storage

In medium-scale combustion plants a broad range of agrobiomass assortments with different bulk densities, energy densities and shapes (chipped, chopped, pelletised agrobiomass) are applied. Experience from other projects as well as from the field tests performed within the AgroBioHeat project have shown that harvesting and fuel storage can have a significant impact on the fuel quality and thus on combustion related properties of the fuel. Therefore, although it is not part of the combustion plant itself, some aspects regarding the harvesting should also be considered here.

Regarding agricultural residues (e.g. straw) and energy crops like miscanthus the harvesting time can have a significant influence on the chemical composition of the fuel, especially regarding K, S and Cl contents. Moreover, storage on field before to deliver to the plant may, depending on the weather conditions, also have an impact on the fuel quality. In case of rain fall during storage on field for instance, K and Cl can be partly washed out (leached) which improves the combustion behaviour. On the other side, storage can also change the strength of the fibers of herbaceous fuels, which may affect the operation of shredders at the plant. These aspects have to be considered during plant design.

Especially when the agrobiomass is collected from the ground it has to be taken care that contaminations with soil and/or stones are minimized respectively avoided. Such contaminations may significantly increase the ash content of the fuel and therefore can cause problems during combustion and de-ashing. Moreover, stones dragged with the fuel into the combustion plant, can cause severe problems in the fuel feeding and the de-ashing system.

Therefore, it is important that harvesting and agrobiomass collection systems are applied which avoid contaminations with soil and stones. Moreover, fuel storage in intermediate storages and on-site shall be done on paved ground so that also during fuel manipulation contaminations with mineral impurities are avoided.

3.3. 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 agrobiomass 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.

3.4. 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 apply 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 agrobiomass 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.

3.5. Application of advanced air staging concepts

Modern medium-scale combustion plants are typically based on air staging concepts and in many cases also implement flue gas recirculation for fuel bed and combustion chamber temperature control. To be suitable for agrobiomass utilization, the aspects described in the following are of relevance.

3.5.1. 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 and therefore, no secondary air should be injected right above the grate or along the fuel bed surface. 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 900 and 1,100°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 keep the NO_x emission limits. 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.

3.5.2. Air staging concept

The primary air ratio respectively the air ratio in the fuel bed should be at values of about 0.7 or even lower in order keep the fuel bed temperatures on a low level. If flue gas recirculation below the grate is applied, the oxygen supplied with the recirculated flue gas has to be considered when defining the primary air ratios. 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.

To reduce NO_x emissions, the air ratio in the reduction zone above the fuel bed (including also a certain false air intake which typically happens via the fuel feeding and the de-ashing system) should be between 0.8 und 0.95 and temperatures between 900 and 1,100°C should prevail in this zone. With these conditions NO_x reduction by 30 to 40% can typically be achieved.

At a given total excess air ratio (typically values between λ = 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. This is especially of relevance for a low-emission operation at partial load.

As mentioned above, 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).

Finally it shall be noted that also medium-scale combustion technologies based on extremely staged combustion (concept as presented in section 2.4.3) are offered on the market. These systems show the lowest gaseous and particulate matter emissions and the highest efficiencies among fixed-bed biomass combustion systems.

3.5.3. 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 agrobiomass assortments 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.

3.6. Avoidance of false air intake

An exact control of the combustion air flows is essential for the implementation of an appropriate 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.

3.7. Boiler design, boiler cleaning and additional heat recovery units

In medium-scale combustion systems typically gas-tube boilers are applied (flue gas flows inside the boiler tubes and the water of the heating cycle outside the boiler tubes). The flue gas temperatures at boiler outlet are typically in a range between 150 and 180°C (at full load). To enhance the thermal efficiency of a plant, also economisers, which are often designed as water tube heat exchangers, can be implemented downstream the boiler. For fuels with high moisture contents (more than 30 wt% w.b.) and if sufficiently low heating water return temperatures prevail (e.g. 40°C), flue gas condensation units can be applied to recover a part of the latent heat by condensing water vapors contained in the flue gas. Combining these heat recovery measures, thermal efficiencies of more than 100% (related to the NCV of the fuel) can be achieved. However, regarding the implementation of economisers low-temperature corrosion related limitations have to be considered (see below) and in case of utilization of agrobiomass assortments with high S and Cl contents, also the formation of acidic condensates in flue gas condensers has to be taken into account.

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, which is the typical case for the targeted capacity range 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 Cl content of the fuel also the risk for low temperature corrosion increases. According to literature, low temperature corrosion is most probably induced by depositions of corrosive hygroscopic salts. In [3] it is recommended to keep the gas-side boiler and economiser 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.

3.8. Secondary measures regarding emission control

In general, primary and secondary measures for emission reduction should always be combined and secondary measures should only be applied if optimized primary measures are not sufficient to keep the respective emission limits.

Due to the high variation ranges of possible ash contents and especially K-contents, secondary dust emission control measures are needed. For most agrobiomass fuels the application of electrostatic precipitators (ESP) can be recommended. These ESPs must be designed (filter volume, gas velocities, voltage and current to be applied) under consideration of the expected increased fine particulate matter emission levels compared with wood combustion. Moreover, they should be equipped with efficient automated cleaning devices for the spraying and the precipitation electrode, which should be operated

[3] BRUNNER T., OBERNBERGER I., RAMERSTORFER C., KANZIAN W., 2018: Evaluation of the Low-temperature Corrosion Potential of Flue Gases from the Combustion of Wood and Non-wood Fuels. In: Proceedings of the 26th European Biomass Conference and Exhibition, May 2018, Copenhagen, Denmark, ISBN 978-88-89407-18-9, ISSN 2282-5819, pp. 430-439, ETA-Florence Renewable Energies (Ed.), Florence, Italy

more frequently than during wood combustion in order to maintain a high long-term precipitation efficiency.

However, experience from realised agrobiomass combustion plants as well as the results of field test runs performed within AgroBioHeat show that for fuels with a very high potential regarding formation of fine particulate matter emissions such as straw a reliable highly efficient long-term operation of ESPs can usually not be maintained. Therefore, for straw combustion plants, baghouse filters are more suitable since they represent the most efficient technology for particle precipitation. Baghouse filters should be combined with upstream cyclones or multi-cyclones in order to precipitate coarse fly ash particles and to remove glowing charcoal particles entrained from the fuel bed, which could harm the filter material (fabric materials are usually applied in baghouse filters).

Regarding NO_x emission reduction, selective non-catalytic reduction (SNCR) is state-of-the-art. However, experience and test run data from the AgroBioHeat project indicate that for agrobiomass fuels typically an optimized air staging concept is sufficient to keep the NO_x emission limit defined in the medium combustion plant (MCP) directive.

3.9. 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. Therefore, the application of much more sensors and measurements instruments is needed than for instance in small-scale residential boilers.

Optimised state-of-the-art process control concepts rely on a load control, a combustion control, furnace pressure control and a furnace temperature control. Load control is thereby realised by the adjustment of the primary air supply and the fuel supply with respect to the load demand. Modern medium-scale combustion plants should thereby show a load modulation capability between 30% and 100% of the nominal boiler load. Combustion control relies on λ control or CO/λ-control (see also section 2.9) whereby the secondary air injection usually is varied to achieve defined oxygen contents in the flue gas downstream the boiler. The furnace pressure is controlled by the flue gas fan whereby usually the underpressure levels are adjusted to the boiler load (lower underpressure at lower boiler load). Finally, furnace temperature control can be realised by the adjustment of flue gas recirculation to achieve defined set values for the furnace temperature measured in the secondary combustion zone.