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Combustion of Solid Biofuels: Problems and Solutions

Bachelor Thesis

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Declaration

I hereby declare that this Thesis entitled “Combustion of Solid Biofuels – Problems and Solutions” is my own work and all the sources have been quoted and acknowledged by means of complete references.

In Prague, 21. 4. 2017 ……………………………………..

Denisa Beňová

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Abstract

The use of fossil fuels for combustion in order to obtain energy has a negative impact on the environment in the form of releasing large amounts of pollutants into the atmosphere. Just the polluted environment and the exhaustion of fossil fuels leads mankind to replace these sources with renewable alternatives such as for example plant biomass. Solid biofuels made from biomass can be used for direct combustion to produce energy for heating the buildings, water heating, etc.

This Bachelor Thesis entitled "Combustion of Solid Biofuels: Problems and Solutions" was written in the form of literature review from mainly scientific articles obtained from professional web databases. The work summarizes information about the combustion process, available combustion facilities that have different combustion bed technology, such as fixed-bed combustion or fluidized-bed combustion - there are also improvements to available technologies. Each current combustion technology has its advantages and disadvantages that have been extensively analysed in the present work. The Thesis also describes the combustion process of biofuels which, comparing to fossil fuels such as coal, do not produce net addition of carbon dioxide, have low sulfur and nitrogen content. On the other hand, the combustion process is not unproblematic – resulting problems are primary associated with the composition of the material used for biofuel and affect operation of combustion devices that have been discussed. Problems arising are slagging and fouling, corrosion, ash agglomerations and pollutant emissions. The Thesis presents options and solutions to prevent or minimize these problems.

Key words: biomass, combustion process, boilers, slagging, fouling

Abstrakt

Využívání fosilních paliv ke spalování za účelem získání energie má negativní dopady na životní prostředí v podobě uvolňování velkého množství škodlivých látek do ovzduší. Právě znečištěné prostředí a vyčerpatelnost fosilních paliv vede lidstvo k nahrazování těchto zdrojů zdroji obnovitelnými jako je například rostlinná biomasa. Biomasa a z ní vyrobená tuhá biopaliva se dají přímým spalováním využít k produkci energie určené k vytápění budov, ohřevu vody, apod.

Tato bakalářská práce na téma „Spalovaní tuhých biopaliv: problémy a řešení“ byla sepsána formou literární rešerše z především vědeckých článků, získaných z odborných databází. V práci jsou shrnuty informace o procesu spalování, dostupných spalovacích zařízení, které používají různou technologii jako jsou roštová nebo fluidní ohniště, také existují vylepšení pro dostupné technologie. Každá současná spalovací technologie má své výhody a nevýhody, které byly v práci podrobně analyzovány. Práce dále řeší spalování biopaliv, u kterých, oproti fosilním palivům jako je uhlí, nevznikají přidané hodnoty oxidu uhličitého, je zde i nízký obsah síry a dusíku. Na druhou stranu není proces spalování bezproblémový, vznikají při něm problémy spojené se složením materiálu použitého pro biopaliva a ovlivňující provoz spalovacích zařízení, které byly též diskutovány. Vyvstávajícími problémy jsou struskování a zanášení, koroze, aglomerace popela a znečišťující emise. V práci jsou uvedeny možnosti a řešení prevence nebo minimalizace těchto problémů.

Klíčová slova: biomasa, spalovací proces, spalovací zařízení, struskování, zanášení

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1. Introduction

Environmental problems caused by fossil fuels, rising prices and gradually exhausting become the focus of research and socio-political attention (Dam et al., 2008). Moreover, the environmental issues that can cause serious problems such as global warming, acid rain and urban smog due to the production of emissions from fossil fuels combustion have tempted the world to try to reduce carbon emissions by 80% and try to substitute these sources by less harmful choices such as utilizing a variety of renewable energy sources for example biomass. Also, biomass must be utilized in sustainable way (Saidur et al., 2011). Biomass consists of compounds resulting from photosynthetic processes (Bridgwater, 2012) and it is substitute to fossil fuels for both heating and electricity generation (Luque et al., 2008). Moreover, biomass is very popular source of energy in rural areas where it is often the only accessible and affordable source for the local people, according to Saidur et al. (2011).

The biomass combustion can take place in various reactors with different technologies such as fixed-bed and fluidized-bed combustion (Khan et al., 2009; Saidur et al., 2011). Moreover, there are new or developed technologies that can improve efficiency of existing reactors or for example can preventing problems of pollutant emission (Abuelnour et al., 2014).

The biomass (wooden, herbal even agricultural) is characterized by many aspects, which influence the whole combustion process and associated problems such as fouling, slagging, agglomeration and corrosion (Repsa et al., 2011). These problems are ash-related problems that should be examined when fuels are used, since they can lead to reduced efficiency, capacity and operation of the facilities, thereby increasing the power cost (Vamvuka et al., 2009). Another problem connected with biomass combustion are pollutant emissions (Wielgosiński et al., 2016).

This Thesis provides description of combustion reactors and comparison of their technical parameters, advantages and disadvantages. Further it investigates arising problems during combustion of solid biomass biofuels and possible minimization or prevention methods.

2. Aim of the Thesis

The aim of this Thesis was to summarize scientific information about combustion of biomass based solid biofuels, and specifically to describe and analyse combustion technologies, to discuss the main problems during combustion and to present appropriate solutions for reduction or prevention of arising combustion problems and thereby destruction of combustion technologies.

3. Methods

The present Thesis was written as a literature review consisting of five chapters, there the main chapters are: Combustion process and technologies, Problems during combustion and Solving problems with combustion of biomass.

The Thesis was elaborated according to the manual of the Faculty of Tropical AgriScience for writing Bachelor's Thesis and all literature is cited in by the mandatory rules of the Faculty.

Literature review preparation was based on searching for scientific articles from web databases Science Direct, Web of Science, EBSCO and others. Most of them come from well-known journals like Fuel, Renewable and Sustainable Energy Reviews, and Biomass and Energy journals. The search for scientific information was done through the key words such as: Biomass, Combustion technologies, Boilers, Slagging, Fouling and others with use of Boolean operators. The gathered information was processed and analyzes. Some information, for example advantages and disadvantages of the combustion technologies was worked out to the form of lucid tables.

4. Literature review

4. 1. Biomass

Biomass is a source of energy used for the centuries till nowadays and the term includes any organic matter which is derived from plants even animals. This Thesis is focused on plant biomass. That is plant materials such as wood from forest, crops – which could be intently grown energy crops or for example wild grasses or weed, seaweed/ algae, material left over from agricultural and forestry processes (Saidur et al., 2011). The energy of biomass originally comes from the sun which initializing process of photosynthesis. Plants convert by this process energy from the sun to chemical energy and that is fixed or stored in the form of terrestrial and aquatic vegetation (Abbasi & Abbasi, 2009). Plants through photosynthesis internalize carbon dioxide from the air and transform it into other carbon containing molecules, mostly sugars. So these sugars are called carbohydrates and stored in plants and animals or in their residues are called bio-energy. Due to carbohydrates, which means energy, is biomass classified as materials that can be used as an energy source in many ways – combustion, anaerobic digestion, pyrolysis etc. Biomass is considered as a renewable energy source because its supplies are not limited. There will always be threes and crops to grown, residues from agriculture and also wastes will always exist (Saidur et al., 2011).

4.1.1 Composition of biomass

Important specific of biomass is its composition which is variable due to a kind of biomass. Plant biomass (herbal or wooden) contains varying amounts of cellulose, hemicellulose, lignin, extractives, lipids, proteins, simple sugars, starches, water, hydrocarbons, ash and other compounds. Two large carbohydrate categories that have significant value are cellulose and hemicellulose (the lignin fraction consists of non-sugar type molecules). These carbohydrate groups determine the calorific value of the fuel. The combination of these biomasses is called ‚lignocellulose'– in Chyba! Nenalezen zdroj dkazů. are shown some types of biomass. It comprises around half of the plant matter produced by photosynthesis and represents the most abundant renewable organic resource on Earth (Perez-Garcia et al., 2005; Demirbas, 2005).

Table 1 Lignocellulosic constituents of some biomass examples

Lignocellulosic residues	**Hemicellulose (%)**	**Cellulose (%)**	**Lignin (%)**	**Ash (%)**
Nut shells	25-30	25-30	30-40	NA
Rice Straw	24	32.1	18	NA
Barley Straw	24-29	31-34	14-15	5-7
Bamboo	15-26	26-43	21-31	1.7-7
Elephant grass	24	22	23.9	6
Hard wood	31.3	45.3	21.7	2.7
Soft wood	24.4	45.8	28	1.7

Source: Saidur et al. (2011)

4.1.2 Biomass as a fuel

Biomass is an attractive renewable fuel for utility boilers. When it is used directly in an energy application without chemical processing then is combusted. Direct combustion and co-firing with coal for electricity production from biomass has been found to be a promising method in the nearest future. The supply is dominated by traditional biomass used for cooking and heating, especially in rural areas of developing countries (Demirbas, 2005; Saidur et al., 2011). Biomass presents some advantages such as its neutrality concerning CO_2 emission during its life cycle or its low N and S content that entails low NO_x and SO_2 emissions. Nevertheless, it also presents some disadvantages, being one of the most important the generating of solid wastes. Ash presence is highly negative for the combustion process as it involves energy efficiency losses and higher maintenance expenses due to unburns and depositions – slagging and fouling – that cause thermal resistance in heat exchangers, corrosion phenomena and increase of fumes and aerosol emissions (García et al., 2015). In addition to carbon neutrality of biomass, when we burn biomass matter, or use it after converting to other types of solid fuel, we release only that carbon to the atmosphere as CO_2 which the biomass had recently captured from atmosphere during its photosynthetic growth. So there is no net addition of CO_2. In contrast when we burn fossil fuels we make a net addition of CO_2 to the atmosphere because fossil fuels are derived from plants and animals that had lived millions of years back. In that era the plants and animals had sequestered billions of tons of carbon over several thousand years. By burning large portions of that carbon per year we have released (and are continuing to release) enormous quantities of CO_2 within a very short time of about 200 years. The Earth´s environment cannot sequester this much carbon at the rate at which it is being released by fossil fuels. So using of fossil fuels led to climate change, causing a lowering in the ocean pH and others negative issues (Abbasi & Abbasi, 2009).

This Thesis is related to solid biofuels made from plan biomass. The energy use of solid biofuels in the processes of direct combustion finds increasing interest of consumer. The European Committee for Standardization, CEN (TC335) has prepared 30 technical specifications for solid biofuels - the classification of solid biofuels is based on their origin and source. The fuel production chain of fuels shall be unambiguously traceable back over the whole chain. Solid biofuels are divided into following sub-categories for classification according to origin: woody biomass, herbaceous biomass, fruit biomass and blends and mixtures. The purpose of classification is to provide the possibility to differentiate and specify biofuel material based on origin with as much detail as needed. The most significant properties are normative, and shall be stated in the fuel specification (Alakangas et al., 2006; Kraszkiewicz et al., 2015).

4.1.3 Briquettes and pellets

Biomass compaction (densification) represents the technology for conversion of biomass into solid fuels in a shape of briquettes and pellets. There is lot s of possible materials to be used as fuel like wood, energy crops, which has the potential to be used as feedstock for solid biomass fuel production in agriculture, for example common reeds are important natural biomass resource. The harvested energy crop stalk biomass is a material of low bulk density (60 – 80 kg/m^3), therefore compacting of biomass is one of the important technologies for effective handling, transport and storage of this fuel material. The quality and strength of the compacted mass depends on the physical properties of the material, applied force and other biomass characteristic (Repsa et al., 2011).

The technology used for binderless biomass - a briquetting includes machines based on screw and piston-pressed technology. Biomass in screw-pressed technology is extrude continuously by a screw through a die, which is externally heated to reduced friction. With piston-press technology, biomass is punched or pushed (corresponding to the impactor hydraulic technology) into a die by reciprocating armor plunger by high pressure (Repsa et al., 2011).

Furthermore, palletization improves the volumetric energy content of the biomass and lowers the cost and carbon emissions associated with transportation and handling; regularly shaped pellets can be handled more easily than chips; energy requirements are lower for milling pellets to small particle size for pulverized fuel boilers; white wood pellets have standardized specifications and so can meet the stringent requirements of the utility companies to minimize issues of deposition and corrosion. Pellets for non-industrial use (i.e. fuel for smaller appliances for domestic, small commercial and public sector building installation) are covered by European standard 14961-2. This is sub-divided into three main classes: Class A1-covers pellets manufactured from virgin timber and chemically untreated wood residues and is low in ash, nitrogen and chlorine. It consists of virgin sawdust from the stem wood (bark removed) or untreated timber. Class A2 is similar to A1 but with slightly higher ash, nitrogen and chlorine levels and largely consists of tree chippings, including bark. Class B covers pellets containing some proportion of chemically treated and used wood with heavy metal content below specified threshold levels and uses recycled wood. Class C is not suitable for these applications and is contaminated by paint or preservative. It must be burned in industrial plants (Lestander et. al., 2012; Gudka et al., 2016).

4.2. Combustion of biomass

Combustion of biomass is environmental friendly way to obtain energy for heating even electricity due to the no net addition of CO_2 (Buczyński, 2011). Attention should be paid also on thermal (chemical and physical composition) properties of biomass. Each type of biomass has specific composition. The most studied properties which influence combustion are moisture content, ash content, fixed carbon and volatile matter content, elemental composition, calorific value and ignition time. These biomass properties may cause design and operational problems on the combustion facility and for this reason it is necessary to know what is happening with biomass during the combustion process in order to find out how to forestall destruction of facilities, how we should treat the material and how we could influence the combustion process to obtain maximal efficiency from solid biofuels (World Bank, 1999; McKendry, 2002a; Chang et al., 2012).

4.2.1 Moisture content

The moisture content definition according to the World Bank (1999) - is „The moisture content of biomass is the quantity of water in the material, expressed as a percentage of the material's weight. This weight can be referred to on wet basis, on a dry basis, and on dry-and-ash-free basis“.

There are two types of moisture content that are in study field. Intrinsic moisture – type of moisture which is not influenced by weather effects and it is chemically bounded in the material. The other is extrinsic moisture – moisture which is influenced by weather especially during harvesting of biomass that moisture typically evaporates during drying of material. For combustion is suitable to use material with moisture content less than 50%, so could be said, that lower the moisture the higher the calorific value for producing energy during combustion of biomass (McKendry, 2002a). On the other hand, technologies for the thermal conversion may use material with higher moisture but it will affect negatively the energy balance of the conversion process, as it was mentioned above and disturb the course of pyrolysis, as the necessary temperature is taken to the evaporation of water. So the best material for thermal conversion is woody and low moisture content (Chang et al., 2012).

4.2.2 Ash content

During the thermal decomposition of the fuel arise solid residues which are called ash. Ash is one of the standard parameters for solid biofuels and it is the inorganic uncombustible part of fuel which left after complete combustion, containing the bulk of the mineral fraction of the original biomass (Khan et al., 2009). Ash content also affects the cost of handling and processing and the cost of converting energy from biomass (McKendry, 2002a).

The composition of biomass ash is strongly dependent on the species and part of the biomass plant. The available nutrients, soil quality, fertilizers and weather conditions have significant impact on the contents of potassium, sodium, chlorine and phosphorus especially in agro-biomass ashes (Saidur et al., 2011). Normally the ash content of biomass fuels ranges from 2 to 20% depending on growth conditions and handling. Inorganic material in biomass can be divided into two fractions, one of which is inherent in the fuel and the other is added to the fuel through processing steps. The major inherent ash forming elements in biomass include silicon (Si), aluminum (Al), titanium (Ti), iron (Fe), calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), sulfur (S), chlorine (Cl) and phosphorous (P). The later, adventitious materials originated from skidding and other operations whereby soil is incorporated into the fuel. It could often makes up a major fraction of the ash content of fuels. Its composition is typically different from that of the inherent materials, as it is the mode of occurrence of the elements. An example could be alumina arising from the incorporation of sands, clays, and other soil particles, and potassium incorporated in feldspars with relatively little contribution to alkali reactions leading to fouling other than by inertial impaction and sticking of particles (World Bank, 1999; Nutalapati et al, 2007; Khan et al., 2009).

Generally, biomass fuels can be divided into three groups on the basis of their main ash composition:

- Biomasses with Ca, K rich and Si lean ash – generally the ash of woody biomass is typically rich in calcium (Ca) and potassium (K).
- Biomasses with Si rich and Ca, K lean ash – most fuels in this group belong to herbaceous or agricultural biofuels. Some of these fuels, like straw of cereals have also relatively high potassium (K) and chlorine (Cl) contents.
- Biomasses with Ca, K and P rich ash – sunflower stalk ash and rapeseed expeller ash from food production are examples (Saidur et al., 2011).

With high ash containing fuel, an efficient dust removal system becomes a must to handle particulate emissions. Also, high ash percentages lower the calorific value of the fuel. High alkali P and Si content typically gives low ash melting temperatures while Mg and Ca increase ash melting temperature. Although a major fraction of low melting point alkali is released into gas phase, the part left in the ash may delivered detrimental effects (bed agglomeration) during combustion. Ash sintering, softening, and melting temperatures can differ significantly among biofuels, and this characteristic is essential in determining temperature control to avoid sintering or slagging. Typically, grasses and straw have mineral fraction leading to low melting temperatures (Khan et al., 2009).

4.2.3 Fixed carbon and volatile matter content

Energy of the fuel is composed of two components - fixed carbon and volatile matter. The volatiles content from the solid biofuels are contained in gas resulting from the combustion – by heating the material at 950 °C for 7 minutes volatile matter starts to show up. The fixed carbon content is the amount of material remaining after the releasing volatile substances, in this component is not included ash and moisture content. During examining the components of volatile matter and fixed carbon is main interest part in the following elements – carbon (C), oxygen (O), nitrogen (N), hydrogen (H), sulfur (S) – these are particularly important for the formation of emission and arising compounds which may damage combustion device for example by slagging and fouling. If we add to this content analysis an analysis of the ash, we will get a final analysis of the fuel that contained key information which may indicate a reaction of the material during combustion process (McKendry, 2002a).

4.2.4 Calorific value

Fuel calorific value, also called heating value, is an indication of the energy which is chemically bound in the fuel, with reference to a standardized environment. Standardization mainly relates to temperature systems and products of combustion (McKendry, 2002a). Gross calorific value is basically the energy content on a dry basis. Net calorific value is calculated by subtracting energy needed to evaporate the moisture content of the fuel. Biomass fuels have lower calorific values compared to coal. Carbon and hydrogen tend to raise the calorific value while oxygen decreases it. The lignin content of the lignocellulosic fuel generally is strongly correlated with calorific value. The gross calorific value of lignin is reported to be higher than of cellulose and hemicellulose. The latter has a lower calorific value due to its higher degree of oxidation (Khan et al., 2009).

4.2.5 Ignition time

The ignition delay or ignition time is extremely dependent on the combustion parameters such as oxygen concentration and oxidant temperature. In biomass combustion, the ash and moisture contents in the fuel cause ignition and combustion problems. The ignition delay almost depends on the oxygen concentration at high temperature of oxidant (1,000 °C) and highly dependent on the oxygen concentration at low temperatures (600 °C). At low oxygen concentrations (5%) of the oxidizer and low temperature 600 °C, the wood pellets did not ignite within 5 min. In the larger combustion volume, the ignition time was almost independent on the oxygen concentration when the oxidizer is preheated to 1,000 °C. Also, it was reported that when oxidizer was preheated up to 1,000 °C and the oxygen concentration enhances up to 21%, delay time to flaming ignition does not occur. When oxygen concentration increases at a low oxidant temperature (800 °C) the delay time decreases (Abuelnour et al., 2014). For better view see Figure 1.

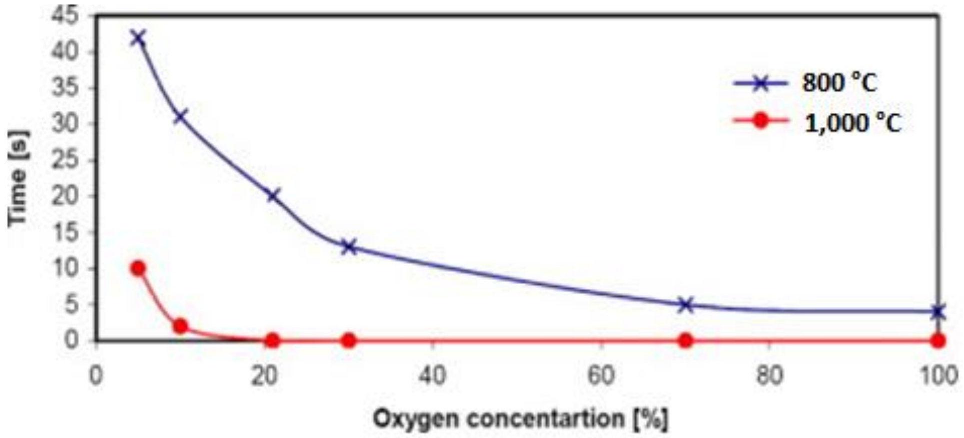

Figure 1. Ignition delay for different O_2 concentrations and oxidant temperature.

Source: Abuelnour et al. (2014)

4.3. Combustion process and facilities

Khan et al. (2009) describe biomass combustion like a complex process consisting of consecutive homogenous and heterogeneous reactions.

The process of combustion includes four-stage principles. The first stage is drying, this stage is characteristic by water evaporation occurs from material. Second is pyrolysis and reduction where starts the material decomposition into volatile gases and solid char. Third is the combustion of volatile gases above the fuel bed – these gases are produced by pyrolysis, reduction burn above the fuel and in this phases showing the well-known yellow flame. Last stage is combustion of solid char in the fuel bed which is combusted on the grate and its burning is characterized by low blue flame and glowing of char pieces on the grate (World Bank, 1999). The biomass combustion process can also be briefly summarized as follows. When heating wood or briquettes from wood (biomass), its consistence start to hydrolyse, oxidize, dehydrate, and pyrolysis with increasing temperature forming combustible volatiles, tarry substance, and highly reactive carbonaceous char. At the ignition temperature of the volatiles and tarry substance, exothermic reaction known as combustion begin. Resinous compounds and decomposition products of cellulose, hemicelluloses, and lignin, together with water vapour are stripped off, and then undergo both partial to complete combustion in the flaming zone. During the smoldering process, enough heat is produced to propagate the charring process as well as the release of additional volatile (wood) decomposition products. Composition and physio-chemical properties of the fuel are the determining factors for duration and rate of each of the above – mentioned steps. Influencing properties include the atomic structure and pathways for the movement of moisture content, hemicelluloses and lignin contents. In terms of process condition, heating rate and excess air ratio are the most important parameters (Khan et al., 2009).

4.3.1. Importance of furnace

In the combustion process, which takes place in the furnace, chemically bound energy of the material is converted into thermal energy in the form of hot flue gas. During the combustion of the fuel may come to pass energy losses, which are caused by the following factors: energy loss through leaky furnace wall, the losses associated with the ashes - the thermal energy from the hot ashes has not been sufficiently released. Further unburned particles - energy from which was also not released. Finally, it is an energy loss in the form of unburnt gases from the pyrolysis and CO in the flue gas from the combustion. Combustion efficiency is mainly determined by the completeness of the combustion process and the amount of heat loss from the furnace (World Bank, 1999). While the entire process means that the vast majority of combustion particles are burned completely, and it is one of the main indicators through the quality and efficiency of combustion which could be determined (Cha et al., 2013).

For the best result, more than theoretically minimal amount of air is required. The excess air factor (λ, lambda) indicates the ratio between the real air supply and the air that is theoretically needed for combustion. At stoichiometric combustion ($\lambda = 1$) supplied air is just sufficient to burn all combustible particles. The higher the value of lambda, the lower the temperature of the flue gas leaving the furnace. For the effectiveness of heat exchanger, it is important that the gas temperature is as high as possible. Temperature is the highest, if lambda is equal to 1, but in practice this is not achieved, its value is in most cases higher than 1. The optimal value for lambda depends on the furnace, the type of fuel and the applied combustion system. Typical values for woody solid biofuels are in the range $1.6 < \lambda < 2.5$. In other combustion facilities designed primarily for burning coal, this parameter may rises to 5, which detracts from the efficiency of heat transfer (World Bank, 1999; Cha et al., 2013).

4.3.2 Importance of heat exchanger

Heat exchangers are a very important part of the boiler. Selection of a suitable heat exchanger is one of primary necessity in relation between combusted material and the reactor. Construction of the exchanger should be highly compact in relation to processing parameters such as temperature, fuel composition and suitable to potential operational problems. If the flue gas temperature is around 500 °C or higher, it is preferable to use smooth surfaces for heat transfer. If the flue gas is below these temperatures or significantly lower, a standard heat exchange surface is used. The smooth surfaces with high resistance to destruction mainly include ceramic materials that exhibit good properties at high temperatures - not corrode and not slagging so much – the talk is about temperatures up to 1,400 ° C. They could be techniqually used at lower temperatures, however, it is economically disadvantageous and thus these materials are used in the combustion of fuel at high temperatures. Mainly because of the high cost of ceramic materials, most reactors using heat from metallic materials which can withstand temperatures up to 1,000 ° C (Kilkovsky et al., 2014).

4.3.3 Combustion technologies

Devices for biomass combustion are mainly called boilers. There are many available technologies for combustion primary designed for coal combustion but they are also used for biomass combustion. There are two basic types: fixed-bed combustion and fluidized-bed combustion. Fluidized-bed combustion was generally discovered as the best technology used to burn a fuel with low quality, high ash content and low calorific value. Of course each of the mentioned technologies has advantages and disadvantages (Saidur et al., 2011).

4.3.3.1 Fixed-bed combustion

Fixed-bed combustion systems were for many years the most common devices for combustion of biomass. Fixed-bed system consists of a grate in a combustion room (thereby forming the furnace). Primary air, for combustion of the char, is supplied under the grate. Secondary air, for combustion of the volatile fuel gases themselves, is supplied above the grate. Typical combustion temperature ranges from 850-1,400 °C. The design of furnace requires placement above the grate in biomass-fired furnace due to high content of volatile matter. For the same reason, biomass furnaces demand a higher proportion of secondary to primary air than the coal-fired furnaces (World Bank, 1999). There are four methods of feeding a reactor-these systems can be classified into underfeed, overfeed, spreader and traveling grate stoker methods (Encyclopaedia Britannica, 2012).

Moreover, there are two types of configuration of fixed-bed combustor the first is co-current conversion. There are known states of fuel combustion process as it undergous thermal conversation (drying, evaporation etc.). In this method is fuel placed over these states and layers separated from each other through temperature where a different thermal conversion can be seen (Khodaei et al., 2015). In the case of a co-current (downdraft) configuration, apart from the flame front moving upwards into the fuel, the bed moves downward. The flame front movement is into the fuel bed in the upward direction against the air flow (Mahapatra et al., 2016). Heat radiation and propagation has less influence, because the combustion begins underneath the grate, heat is then retained within the bed and is controlled by a convective flow. Advantages of this method are: high calorific value due to low oxidation, ease feeding of the reactor and a high degree of thermal conversion. On the other hand there are also disadvantages: high level of tar depositing on the reactor walls due to temperature variations that occur in the feeding of the boiler. Furthermore, the high cost of installation and operation of boilers, mainly due to a more complex method of material ignition, design of the burners and air distribution (Khodaei et al., 2015). The scheme of co-current conversion is shown down-on Figure 2.

Second type of configuration is the counter-current where ignition starts at the bed top, and after stabilizing, the flame front propagates downwards opposite to the direction of primary air flow. Primary air from the bottom of the packed-bed is fed through a perforated plate distributor known as the grate, with or without preheating (Khodaei et al., 2015). In the case of counter-current configurations, as solid fuel does not move, the effective propagation rate solely depends on the flame propagation rate (Mahapatra et al., 2016). Advantages of this type of configuration is lower particulate matter formation and lower internal bed temperatures due to a higher oxygen concentration above the bed which consequently leads to lower NO_x formation. Heat released from combustion of biomass at a high temperature on the surface of the bed improves volatile oxidization in freeboard volatiles and helps crack the tar produced through pyrolysis. Disadvantages of this configuration are for example complex mathematical modelling and numerical analysis. This complexity arises due to the more significant importance of radiation and mass diffusion terms at the reaction front (Khodaei et al., 2015). The scheme of counter-current conversion is shown also on Figure 2.

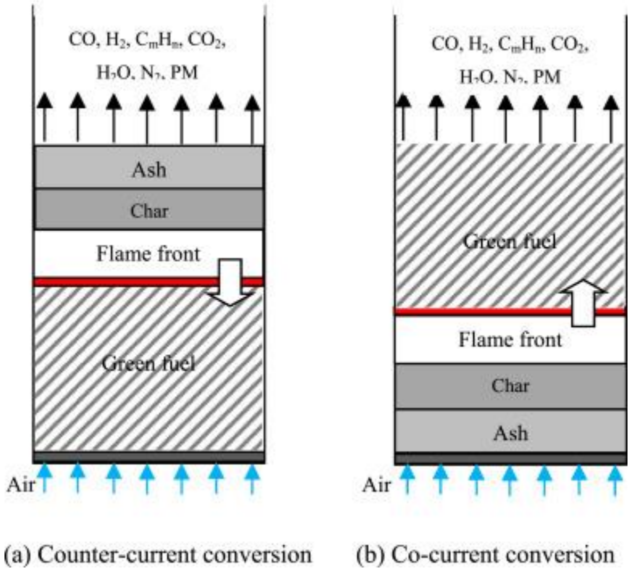

Figure 2. Thermal conversion in two different types of fixed-bed configurations.

Source: Khodaei et al. (2015)

4.3.3.2 Fluidized-bed combustion

According to the studies from Khan et al. (2009) and Saidur et al. (2011) fluidized-bed combustion is emerging as available alternative and has significant advantages over conventional firing system. The fluidized bed boilers have a wide capacity range from 0.5 t/h to over 100 t/h. Among others advantages of fluidized-bed combustion belong uniform temperature distribution, large solid-gas exchange area, high heat transfer coefficients between bed and heat exchanging surface, ability to handle a wide range of fuels having different sizes, shapes, moisture contents, calorific values, stable combustion operation at low temperatures (850°C) and no thermal/prompt NO_x, reduce emission of noxious pollutants such as SO_x – so it has low environmental impact and compact boiler design.

4.3.3.2.1 Atmospheric classic fluidized-bed combustion system (AFBC)

In AFBC also called bubbling bed (BFBC), fuel is crushed to a size of 1 – 10 mm (which could be pellets) depending on the rank of fuel, type of fuel feed and fed into the combustion chamber – under, into or onto the bed. The atmospheric air, which acts as both the fluidization air and combustion air, is delivered at pressure and flows through the bed after being preheated by the exhaust flue gases (Khan et al., 2009). The velocity of fluidizing air is in the range of 1.2 – 3.7 m/s (Saidur et al. 2011). The rate at which air is blown through the bed determines the amount of fuel that can be reacted. In the furnace, an initially stationary bed of solid particles (usually silica sand), located in the bottom part of furnace, is brought to a fluidized state by the primary air which is supplied through a nozzle distributor plate. The bed particles are kept in suspension by the primary air at comparatively lower fluidization velocities. The well defined surface of the bed disappears and the solids concentration decreases continuously with increasing height above the distributor plate. The bed acts as a heat buffer enabling high heat transfer between the particles (Koornneef et al., 2006; Khan et al., 2009). Due to this, the AFBC combustor is less sensitive to variations in of moisture, and is very suitable for biomass and waste firing, with wide variations in the fuel moisture content. This characteristic along with a lower fluidization velocity and high residence time of bed material allows using larger fuel particles and fuels with lower calorific value. The entire size distribution of the feed should have a higher terminal velocity than the fluidization velocity, otherwise it will be elutriated out of the combustor and very large particle sizes will be segregated and therefore, will not fluidize properly. However, even these limitations leave a very large window of feed particle size distribution. The particles of an AFBC are not returned to the bed. Secondary air, if employed, is introduced at the top of the bed (splashing zone) and further higher up (freeboard) through well distributed air inlets over the entire with of the boiler. The temperature normally varies between 760 – 870 °C and is controlled by the internal heat exchanger (Koornneef et al., 2006; Khan et al., 2009; Saidur et al. 2011). Scheme of AFBC/ BFBC is shown on Figure 3.

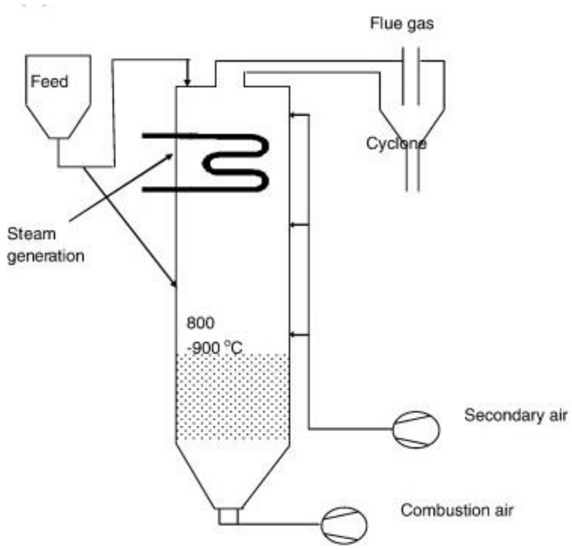

Figure 3 Atmospheric fluidized-bed combustion system.

Source: Khan et. al., 2009

This type of boiler can operate at near atmospheric or elevated pressure and have some essential features: Distribution plate through which air is blown for fluidizing. Immersed steam-raising or water is heating the tubes which extract heat directly from bed. Tubes above the bed which extract heat from hot combustion gas before it enters the flue duct (Saidur et al., 2011).

4.3.3.2.2 Circulating fluidized-bed combustion system (CFBC)

Circulating fluidized bed combustion technology has evolved as upgrade of AFBC to remove some disadvantages of current technology. This technology uses a similar principle as AFBC. Fuel size 6-12 mm together with limestone is inserted into the combustion chamber. These components are suspended in an upwardly flowing air which enters from the bottom of the furnace through the nozzle distribution. The fluidizing velocity in circulating beds ranges from 3.7 to 9 m/s. The balance of combustion air is admitted above the bottom of the furnaces secondary air. The combustion temperature ranges between 840 – 900°C, and the fine particles are elutriated out of the furnace with flue gas velocity 3 – 6 m/s. The particles are then collected by the solids separators and circulated back into the furnace (Saidur et al., 2011; Khan et al., 2009). The scheme of CFBC is shown on Figure 4.

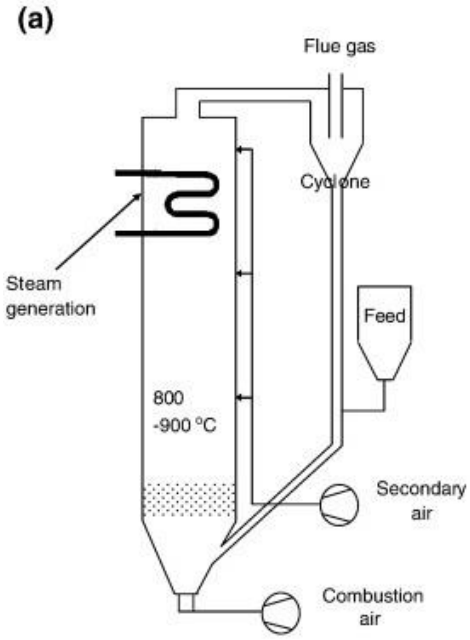

Figure 4. Circulation fluidized-bed combustion.

Source: Khan et al., 2009

According to Saidur et al. (2011) the major performance features of the circulating fluidized-bed system are as follows:

- It has a high processing capacity because of the high gas velocity through the system.
- The temperature during the entire combustion process is relatively constant, about 870°C, mainly due to high turbulence and circulation of solid particles. The low temperature also results in minimum formation of NOx.
- Sulfur present in the fuel is retained in the circulating solids in the form of calcium sulphate and removed in solid form. The use of limestone or dolomite sorbents allows a higher sulfur retention rate, and limestone requirements have been demonstrated to be substantially less than with AFBC combustor

4.3.3.3 Co-combustion of biomass with coal

Co-combustion refers to the combustion of biomass and coal for power production (Saidur et al., 2011). Under the shared combustion there is reduction or, more accurately, partial elimination of the environmental impact due to low content of sulfur and nitrogen in biomass, resulting in a reduction of CO, SO_2 and NO_x, as well as reducing emissions of heavy metals. Coincineration is currently considered as one of the most promising methods for the provision of energy production in general. Coincineration of biomass with coal significantly increase the clean energy ratio of produced electricity to the total consumption of fossil energy. When substituting a certain percentage of coal with biomass it is primarily reducing the greenhouse gas emissions from mining, transportation, and combustion of coal. (Bosák et al., 2015).

Co-combustion of biomass with coal offers the following advantages according to Tabet & Gökalp (2015):

- It is the fastest way to increase the use of renewable biomass for electric power generation.
- It utilizes biomass at higher efficiency in coal-fired plants compared to direct biomass-fired plants.
- It saves capital cost by using existing plant infrastructure.
- It offers environmental advantages mentioned above.

Although co-combustion of biomass and coal represents a cheaper and low risk sustainable energy option (Tabet & Gökalp, 2015). On the other hand, there are disadvantages and related problems with co-combustion of biomass with coal - one of them is increased cost associated with the production and logistics of biomass assurance (Bosák et al., 2015). However, attention must be focused on deposit formation in the boiler and limitations in ash use due to constituents in biomass, especially alkali metals, which may disable the use of ash in building materials. Other problems that could arise are difficulty in fuel handling and storage, decrease in overall combustion efficiency, pollutant emissions, and carbon burnout. Due to undesired changes of ash composition, the share of biomass is usually limited to approximately 20% of the fuel input (Saidur et al., 2011; Tabet & Gökalp, 2015).

4.3.3.3.1 Pressurized fluidized-bed combustion system (PFBC)

Pressurized fluid bed combustion (PFBC) is a variation of fluidized-bed technology that is meant for large-scale coal burning applications. In PFCB, the bed vessel is operating at elevated pressure and high pressure. The off-gas from the fluidized bed combustor drives the gas turbine. The steam turbine is driven by steam raised in tubes immersed in the fluidized bed. The condensate from the steam turbine is pre-heated using waste heat from gas turbine exhaust and is then taken as feed water for steam generation. The PFBC system can be used for cogeneration or combined cycle power generation. By combining the gas and steam turbines in this way, electricity is generated more efficiently than in conventional system. The overall conversion efficiency is higher by 5% to 8%. At elevated pressure, the potential reduction in boiler size is considerable due to increased amount of combustion in pressurized mode and high heat flux through in-bed tubes. PFCB boilers are mainly used in co-firing biomass with coal (National Certification Examination for Energy Managers and Energy Auditors, 2010; Saidur et al., 2011).

4.3.3.4. Advanced technology – Flameless combustion

The demands of energy and pollutant emissions reduction have motivated the combustion researchers to work on combustion improvement. Flameless combustion or high temperature air combustion has many features such as flame stability, low pollutant emission and uniform profiles of temperature compared to the other modes of combustion. Flameless combustion phenomenon has enormous effects on emission reduction and combustion performance improvement. It was observed that when the furnace temperature was around 1,000 °C and the preheated combustion air was about 650 °C the fuel was completely consumed without a visible flame. The results confirmed that combustion was stable, NO_x emissions were approximately zero, low noise and smooth with low carbon monoxide content in the exhaust was reported. In flameless mode, the enthalpy of the reaction zone is more than in conventional combustion because the circled part of thermal energy from combustion products increases the combustion temperature. This takes place du to co-called “Excess Enthalpy Combustion”. Flameless combustion could be characterized as external or internal recirculation and very intensive mixing of the particles inside the combustion chamber.

This technology is used in large volumes of combustion with a relatively uniform distribution of reactive biomass species (Abuelnour et al., 2014).

Combustion takes place with very low concentrations of oxygen. In flameless combustion technique, due to oxygen concentration reduction in the reaction zone, combustion spreads over a large volume, peak temperature decreases, heat flux and thermal efficiency increase and stable combustion is observed. When the conditions inside the chamber are stable and the mode of the flameless starts, the biomass sample is inserted into the reaction zone and kept for a specified duration of time. During the reaction, the temperature of the combustion air is above the auto ignition of the biomass (Li et al., 2012).

The major challenge in using flameless combustion technology is about the design of burner and furnace. Such design determines the effectiveness of the combustion process in the flameless mode, and hence controls the ignition time, temperature uniformity and pollutant emissions. Therefore, it is vital to review and discuss the various designs and methods to achieve flameless combustion for different biomass fuels. Biomass and air combustion were mixed with large amounts of recirculated exhaust gas to dilute the reaction zone. Due to that, the flame temperature decreased and the average temperature of the reaction zone increased. Figure 5 shows the basic principle of the flameless combustion burner used in such study. From this Figure 5Figure 5, it can be seen that the fuel gas recirculation was mainly internal recirculation and the air and fuel were injected to the burner at non-premixed configuration. In addition, it can be noted that the reaction zone is located downstream relatively far from the point of injection. For this reason, low peak temperature of the flame and low oxygen concentration can be found in this area (Abuelnour et al., 2014).

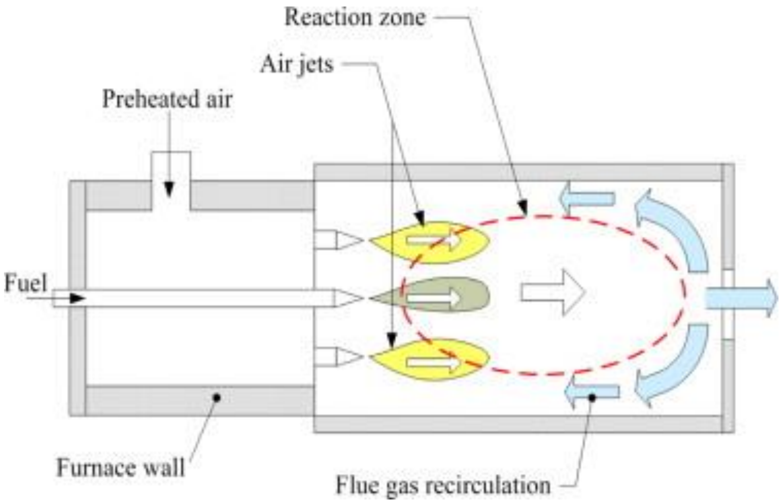

Figure 5. Flameless furnace.

Source: Abuelnour et al. (2014)

As regarding to NO_x emissions it was found that ignition delay decreases and volatiles release enhances. Also it was observed that NO_x emission reduces by 40% when the preheated air temperature increases during the experiment. The level of NO_x emission is proportional to the oxygen concentration in the combustion air and combustion air temperature. At very high combustion air temperature (1,000 °C) the level of NO_x increases rapidly with oxygen concentration in combustion air (Abuelnour et al., 2014). At the oxygen concentration of 70% the maximum level of NO_x emission was reported. At this point, the maximum level of NO_x emission was resulted from two types of combinations; the first combination is between the nitrogen surrounded within the fuel matrix and the oxygen in excess; the second combination is between oxygen and nitrogen from air. Low NO_x emissions are achieved even under high temperature. This is big advantage of the flameless combustion (Choi & Katsuki, 2001).

4.3.3.5 Comparison of combustion technologies

Firstly, in this chapter is given comparison of atmospheric fluidized-bd combustion (AFBC) and circulating fluidized-bed combustion (CFBC), including presentation of the differences in technical parameters of both technologies which are shown in Table 2 , afterwards follows comparison of advantages and disadvantages of all technologies mentioned in the Thesis (see Table 3).

Table 2. Comparison of AFBC and CFBC combustion technologies.

Comparison of Technical Parameters of AFBC and CFBC Combustion Technologies		
Desing parameter	**AFBC**	**CFBC**
Combustion temperature (°C)	760 - 870	840 - 900
Fuel particle size (mm)	1.0 - 10.0	6.0 - 12.0
Fluidization velocities (m/s)	1.2 - 3.7	3.7 - 9.0
Particle concentration	High in bottom, low in freeboard	Gradually decreasing along furnace height
Average steam parameters		
Steam flow (Kg/s) range	36 (13 - 139)	60 (12 - 360)
Steam temperature (°C) range	466 (150 - 543)	506 (180 - 580)
Steam pressure (MPa) range	7.2 (1 - 16)	10.3 (1 - 27.5)

Source: adjusted by author according to Koornneef et al. (2006), Khan et al. (2009) and Saidur et al. (2011).

AFBC was the first type of fluidized-bed combustion introduced in 1970´s and experience over past three decades confirms that technology is well suited to the utilization of 'difficult' fuels containing high portion of moisture, ash and low portion of volatile matter. These fuels are for example wastes (municipal or agriculture) or anthracite, culm and petroleum coke, this technology is well suited for smaller industrial applications. This technology has faced increasing competition from the CFBC variant in recent years; it now maintains a significant position in the market. CFBC technology was derived from AFBC. The technology implementation has changed over time, as the capacity of the installation steadily increased. The result is that it has developed from industrial application to utility applications (Koornneef et. al., 2007; Khan et al., 2009).

In the AFBC combustor, the majority of fuel particles react in the bed with the oxygen in the upward airflow. The lower combustion zone contains a high density of the mix of fuel, sorbent and ash. Refractory protects this part of the furnace from high temperatures as well as corrosion (Khan et al., 2009; Saidur et al., 2011)

The basic difference between AFBC and CFBC is the fluidization velocity, which is higher for CFBC. As a result the solids are entrained in the air flow more equally along the combustor height. The mix is fluidized with primary air. These higher velocities and vigorous mixing in CFBC results in a different heat transfer pattern of the flue gas. The heat transfer and particle concentration gradually decreases along with combustor height and are more equally distributed within combustor as compared to AFBC. This results in more homogenic temperature distribution in a CFBC. Another difference is combustion temperature in these technologies, which is often lower due to poor fuel quality, greater particle size and high moisture content for AFCB (Koornneef et al., 2006).

According to Saidur et al. (2011) the main comparison between CFBC and AFBC are:

- CFBC has higher combustion efficiencies than AFBC due to higher fluidization velocities
- CFBC has better turndown ratio than AFBC
- Erosion of the heat transfer surface in the combustion chamber of CFBC is reduce, since its surface is parallel to the flow in contrast to AFBC, where surface is generally perpendicular to the flow.

Table 3. Analysis of advantages and disadvantages of available combustion technologies.

Technology	Type of reactor	Advantages	Disadvantages
Fixed-bed	Generally	- High ash content feedstock possible (Wernecke, 2000) - High carbon conversion efficiency (Wernecke, 2000)	- High investment for high loads (Wernecke, 2000) - Channelling possible (Wernecke, 2000) - Low specific capacity (Wernecke, 2000) - Long periods for heat-up (Wernecke, 2000) - Large pellets as uniform as possible needed (Wernecke, 2000) - A large amount of deposited carbon (Jing et al., 2006)
	Co-current	- Relatively clean gas is produced (Wernecke, 2000) - High calorific value due to low oxidation (Khodaei et al., 2015) - Easy feeding (Khodaei et al., 2015)	- High amount of tar deposites (Khodaei et al., 2015) - High cost of installation and operation (Khodaei et al., 2015)

Fixed-bed	Co-current	- High degree of thermal conversion (Khodaei et al., 2015)	
	Counter-curent	- Lower particulate mater formation (Khodaei et al., 2015) - Lower internal bed temperature that leads to lower NOx emission (Khodaei et al., 2015) - Improved volatile oxidation that helps crack the tar (Khodaei et al., 2015)	- Extensive gas clean-up needed (Wernecke, 2000)
Fluidized-bed	Generally	- Best temperature distribution (Wernecke, 2000) - High efficiency (Saidur et al., 2011) - Good gas solid contact and mixing (Wernecke, 2000) - High specific capacity (Wernecke, 2000; Saidur et al., 2011) - Tolerates wide variations in fuel quality (Wernecke, 2000; Saidur et al., 2011) - Broad particle-size distribution (Wernecke, 2000; Saidur et al., 2011) - High carbon conversion efficiency (Wernecke, 2000; Jing et al., 2006) - No moving parts in the hot combustion chamber (Koppejan & Loo, 2012) - NOx reduction by air staging works well (Saidur et al., 2011; Koppejan & Loo, 2012) - High flexibility concerning moisture content and kind of biomass (Saidur et al., 2011; Koppejan & Loo, 2012)	- Conflicting temperature requirement (Wernecke, 2000) - High dust content in gas phase (Wernecke, 2000; Koppejan & Loo, 2012) - Slagging, fouling, agglomeration etc. (Saidur et al., 2011) - Loss of bed material with the ash (Koppejan & Loo, 2012) - High investment cost (Koppejan & Loo, 2012) - High operation cost (Koppejan & Loo, 2012) - Utilization of high alkali biomass fuel is critical due to bed agglomeration (Saidur et al., 2011; Koppejan & Loo, 2012)

Fluidized-bed	Generally	- Low excess oxygen raises efficiency and decreases flue gas flow (Saidur et al., 2011; Koppejan & Loo, 2012) - Ability to burn low grade fuel (Saidur et al., 2011) - Comercial designs are available (Wernecke, 2000)	
	AFBC	- Easily starts and shuts down, fast heat-up (Wernecke, 2000) - Easy operating (Wernecke, 2000)	- Pressure drop is high (Wernecke, 2000)
	CFBC	- Very fast heat-up (Wernecke, 2000) - Homogenous combustion conditions in the furnace if several fuel injectors are used (Koppejan & Loo, 2012) - High specific heat transfer capacity due to turbulence (Koppejan & Loo, 2012)	- Low flexibility with regard to particle size (Koppejan & Loo, 2012) - High sensitivity concerning ash slagging (Koppejan & Loo, 2012)
Co-combustion	PFBC	- Low excess oxygen increase efficiency (Koppejan & Loo, 2012) - High NOx reduction by efficient air staging and mixing possible (Koppejan & Loo, 2012) - Very good load control and fast alternation of load possible (Koppejan & Loo, 2012) - Saves capital costs (Tabet & Gökalp, 2015) - Reducing the greenhouse gas emissions from mining, transportation, and combustion of coal (Tabet & Gökalp, 2015) - The fastes wa to use renewable sources for	- Particle size of biomass fuel is limited (Koppejan & Loo, 2012) - High wear rate of insulation brickwork (Koppejan & Loo, 2012) - An extra start - up burner is necessary (Koppejan & Loo, 2012) - Increasing cost associated with the production and logistics of biomass assurance (Bosák et al., 2015) - Difficulty in fuel handling and storage, decrease in overall combustion efficiency, pollutant emissions, and carbon burnout (Saidr et al., 2011; Tabet & Gökalp, 2015) - Due to undesired changes of ash composition, the

Co-combustion	PFBC	power generation (Tabet & Gökalp, 2015)	share of biomass is usually limited to approximately 20% of the fuel input (Saidur et al., 2011; Tabet & Gökalp, 2015)
Advanced technology	Flameless combustion	- Low NOx emission (Choi & Katsuki, 2001) - High efficiency (Abuelnour et al., 2014) - The mass loss during combustion of solid biofuels decrease (Abuelnour et al., 2014) - Ignition delay due to high preheated air combustion and low oxygen concentration (Suda et al., 2002) - CO2 reduction (Rafidi et al., 2008) - Equipment size reduction (Rafidi et al., 2008) - Noise reduction (Abuelnour et al., 2014)	- Flashback and poor combustion stability (Abuelnour et al., 2014) - Tendency to preheat air using recovery heat which incorporates a large - scale heat recovery system to obtain waste heat (Abuelnour et al., 2014)

Adjusted by autor according to the cited references.

4.4. Problems during combustion process

During combustion process are arising problems connected to chemical composition of biomass. The composition of biomass among fuel types are considerable variable, especially with respect to inorganic constituents leading to the critical problems of fouling, slagging, bed agglomeration (in fluidized-bed) and corrosion related problems. Alkali and alkaline earth metals, during combination with other fuel elements such as silica and sulfur, and facilitated by the presence of chlorine, are responsible for many undesirable reactions in combustion furnaces and power boilers (Demirbas, 2005; Natulapati et al., 2007). Also nitrogen can cause problems, because of its impact on NO_x emission (Gudka et al., 2016). Some ash particles produced during solid fuel combustion adhere to surfaces of heat exchanger tubes inside biomass combustion boilers. The ash depositions cause heat transfer inhibition – slagging and fouling (Naganuma et al., 2013). Deposition characteristics can often be related to the composition of the fuel, as a result the bulk ash analysis of the fuel gives a good indication of the fuel behavior in a combustor. But deposition characteristics also depend on temperature and operating conditions of the system (Nutalapati et al, 2007). Biomass combustion is a series of chemical reactions by which carbon is oxidized to carbon dioxide, and hydrogen is oxidized to water. Oxygen deficiency leads to incomplete combustion. Excess air, cools the system. The air requirements depend on the chemical and physical characteristics of the fuel. The combustion of the biomass relates to the fuel burn rate, the combustion products, the required excess air for complete combustion, and the fire temperatures (Demirbas, 2005).

4.4.1 Fouling and slagging

Fouling or deposits are commonly known as the layers of materials (ash) collected on the surface of heat transfer equipment. Slagging characterizes deposits on the furnace walls or other surfaces exposed to predominantly radiant heat. In boilers, these problems are regarded as one of a major issue that can affect the design, life time and operation of combustion equipment, increase the operating cost, decrease boiler efficiency, increase carbon dioxide emissions, deteriorate combustion behavior with higher combustion temperatures, increase nitrogen oxides and carbon monoxide, reduce heat transfer and causes corrosion and erosion (Saidur et al., 2011). Examples of slagging, slagging process and fouling are shown on Figure 6, Figure 7 and Figure 8. The major elements causing fouling and slagging are the essential minerals for plant growth and include silicon (Si), calcium (Ca), potassium (K), aluminum (Al), iron (Fe), magnesium (Mg), titanium (Ti), sodium (Na), phosphorus (P) and sulfur (S). Essential minor minerals make up the trace elements of the biomass, although some also arise through contamination. Waste wood can pose unique problems because of potential contamination from paint, plastic and preservatives (the latter affecting the copper chromium and arsenic concentrations) (Gudka et al., 2016). Ash composition together with sulfur and chlorine contents which facilitates the mobility of many inorganic compounds, in particular alkali compounds including potassium and sodium from alkali silicates that melt at low temperatures (can be lower than 700°C), thus providing a sticky surface for enhanced deposition. Sodium and potassium lower the melting point of ash and, hence can increase ash deposition and fouling of boiler tube (Saidur et al., 2011).

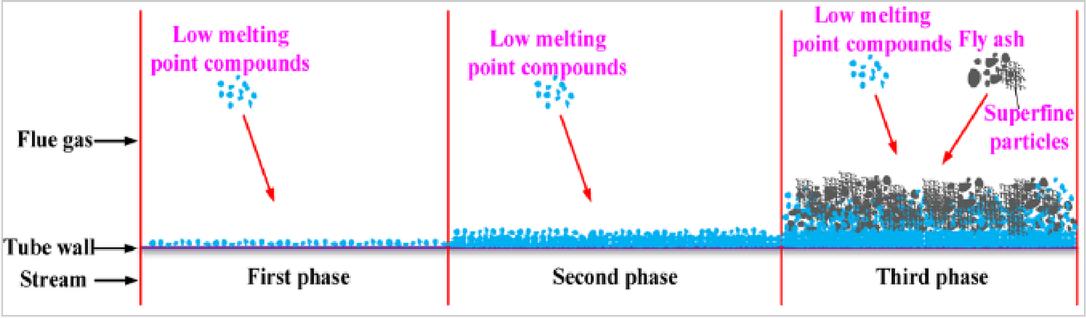

Figure 6. Diagram of the slagging process.

Source: Wang et al. (2015)

Figure 7. Slag body.

Source: Wang et al. (2015)

Figure 8. Fouling on heat exchanger.

Source: IMPO (2013)

Natulapati et al. (2007) made thermodynamic calculations of temperature (temperature range of 500 – 1,600 °C) and combusted material in order to detect fouling and slagging process. The temperature scale was divided into three sections: radiative section (1,600-1,300°C), high temperature fouling section (1,300-900°C) and low temperature fouling section (900-500°C). As the fuel enters into the radiative section, it burns and a part of the inorganic matter evaporates into the gas phase, the other part remains in the condensed phase in the form of solids or melts. The generated gases from the radiative section are taken to the high temperature fouling section and the condensed phase is removed from the system. By estimating the amount of melt phase from the condensed phase, the slagging propensities were estimated in the radiative section temperature range. The gases from the radiative section enter into the high temperature fouling section, where some of the inorganics condense and leads to fouling. The remaining gas phase species were taken into the next stage, which is low-temperature fouling section (900–500 °C) and the condensed phase is removed from the system. By estimating the amount of melt phase in the temperature of 1,300–900 °C high-temperatures fouling were detected. Similarly the melt phase in 900–500 °C gives the low temperature fouling propensities. Gas phase reactions can gives rise to alkali sulphates, and these together with the chlorides are key species responsible in slagging, fouling and even corrosions. Different ash chemistry leads to liquid or sticky ash particles with also form furnace deposits. Slagging is associated with the fusion and sintering of ash particles in the high temperature (radiative sections) of the boiler. Particles entrained in the flue gas impinge on boiler tubes and walls and can adhere depending upon the state of the particle and the surface in question. If either the particle or the surface is molten or sticky then the particle sticks by inertial impaction. The temperature at which the ash softens is determined from the ash fusion test (Gudka et al., 2016).

For making better use of biomass, it's essential to know the fusion characteristics of biomass ash. Standard ash fusibility temperatures (AFT) test is the most common technique to measure the melting temperatures of ash. Traditional AFT test describes the melting degree of ash using four characteristic temperatures which are related to the geometrical shapes of the sample. The characteristic temperatures obtained from AFT are Deformation, Softening, Hemispherical and Fluid Temperature. The AFT method has poor repeatability and it is not suitable method for ash fusion test for biomass. Also, there is another methods that can be used for ash fusion test, i.e. Simultaneous thermal analysis (STA) has been used as an alternative method to analyze the melting properties of chemical substances, but the composition of biomass ash is too complex to be measured by this method. The shift from exothermic to endothermic conditions on the curve is thought to be indicative of melting. However, the shift can be also caused by exothermic chemical reaction, which is not related with melting. So this is also not suitable method to use. Thermo-mechanical analyzer (TMA) can measure the shrinking ratio of samples, which is directly related to the melting degree of ash. TMA has been used to predict the melting temperatures of coal ash and was proven to measure slight presence of melting phase with higher accuracy than AFT test. TMA is applied in analyzing the deposition tendency of biomass ash. It was decided to use TMA method to measure the melting temperatures of different biomass ash and explain the variation of ash characteristics during ash melting (Ma et al., 2016).

4.4.2 Corrosion

Solid biofuels from biomass matter usually contain large amounts of alkali chloride which result in a very corrosive flue gas (Karlsson et al., 2015). Corrosion is the deterioration of intrinsic properties of a material due to reaction with its environment. Corrosion can be caused either directly by gas phase species, by deposits or by a combination of both (Saidur et al., 2011). Example of the corrosion is shown on Figure 9. The deposits on the superheater tubes are often composite of potassium chloride (KCL) and sodium chloride (NaCl) (Karlsson et al., 2015). The corrosion mechanisms in biomass fired boilers can be broadly classified into three classes: corrosion associated with gas species (active oxidation), solid phase corrosion, and molten phase corrosion.

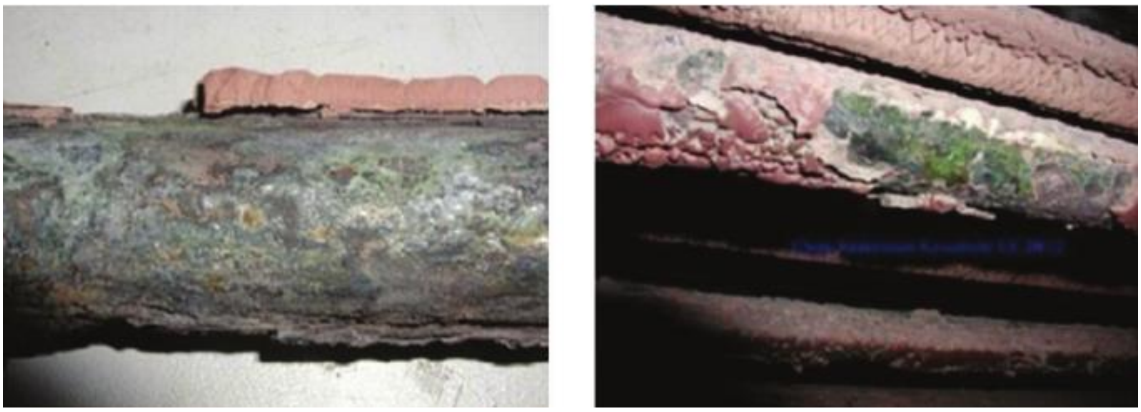

Figure 9. Corrosion from using a high chlorine biomass.

Source: Mudgal et al. (2014)

Another way to remove the effect of chlorine in deposit ash subsequently corrosion is basically focused on the capture of alkali compounds (Saidur et al., 2011). Biomass contains high amounts of potassium (K) and chlorine (Cl), while the content of sulfur (S) is normally relatively low. During combustion these elements are released to the flue gas and significant amounts of alkali chlorides may condense on the heat exchanger tubes forming a chloride-rich deposit. The aggressive nature of alkali chlorides on both low and high alloyed steels has been confirmed. As a consequence, biomass-fired boilers are designed with lower steam temperatures than in corresponding coal-fired plants which lead to lower efficiencies when burning biomass for power generation. Other gaseous species such as hydrogen chloride and water vapor may also affect alloy performance in the superheater region, although their impact is limited compared to the deposition of chlorides directly on the tube surfaces (Viklund et al., 2014).

The corrosive behavior of alkali chlorides towards stainless steel is the formation of alkali chromates. It has been shown that alkali chlorides react with chromium in the initially formed protective oxide on stainless steel, forming alkali chromates. This results in a chromium depleted oxide which is then converted into an iron-rich fast-growing oxide. The oxide has much poorer protective properties as it has higher diffusion rates compared to chromium rich oxides. The chromate formation reaction is not limited solely to alkali chlorides. After the breakdown of the initially protective oxide, the iron-rich oxide formed from the reaction with alkali compounds is susceptible to chlorine-induced corrosion by chlorine ions penetrating the oxide scale. This leads to the formation of transition metal chlorides at the metal/oxide interface causing poor scale adherence (Karlsson et al., 2015).

Another explanation for the accelerated corrosion attack is the active oxidation (Karlsson et al., 2015). Active oxidation of iron and steels occurs when the oxidation scale on the metallic surface has no protective character and chloride – based contaminants strongly accelerate its oxidation rate. It is all about chemical reactions that starts with formation of chlorine from HCl oxidation or upon reaction condensed chlorides with the oxide scale (oxidized metal slices generated by the thermoforming of metal alloys based on iron due to atmospheric oxygen) (Antunes & de Oliveira, 2013) It is suggested that chlorine in gas phase diffuses through micro cracks and pores in the oxide scale, forming volatile metal chlorides in the reducing environment at the oxide/metal interface. The gaseous metal chlorides then diffuse through the oxide, forming metal oxide in the outer part of the scale where the partial pressure of oxygen is higher, releasing chlorine in gas phase. The molecular chlorine formed in thus way has been suggested to diffuse inwards through the scale, to react with the metal again (Karlsson et al., 2015).

4.4.3 Agglomeration

Agglomeration can occur as a result of two phenomena: accumulation of low-temperature-melting salts of potassium and phosphorous; and in the presence of silica from sand and calcium from fuel, potassium phosphate can react with silica forming low-temperature-melting silicates of potassium and calcium while phosphorous bounds with calcium. Agglomeration is responsible for causing defluidization in boilers (Khan et al., 2009). Example of agglomeration process is illustrated on Figure 10.

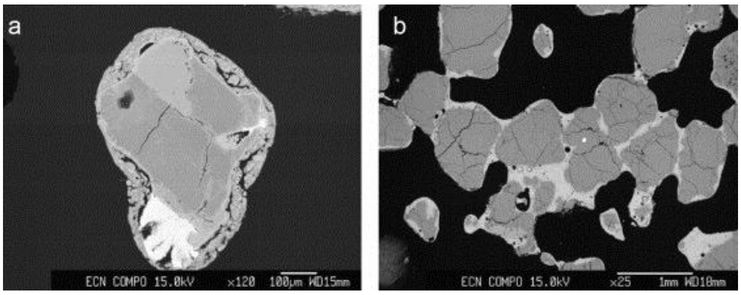

Figure 10. Agglomeration process: (a) Layer built up of ash rich in potassium around a sand particle. (b) Agglomerate formation-binding material rich in potassium.

Source: Saidur et al. (2011)

In AFCB/BFBB, the main reason of agglomeration problems comes from the second phenomenon. In its extreme case, agglomeration leads to unscheduled shutdown of the plant. For these reasons, it's essential that this problem should be brought under control if not totally eliminated (Saidur et al., 2011). Agglomeration may be classified broadly into three types: defluidization induced agglomeration, melt-induced agglomeration and coating-induced agglomeration (Mettanant et al., 2009).

Defluidization induced agglomeration is caused by three mayor causes - Physical or chemical forces between individual particles; Chemical or physical modifications of the solids which are triggered by specific process conditions; Binders (substances that adhere chemically or physically to the solid surfaces) forming a material bridge between particles (Pietsch, 2003). In the beginning of examination of agglomeration it was found that it could be a consequence of defluidization of the bed materials as much as agglomeration could be a consequence of defluidization. External force on particles may be due to liquid deposition on the particles. For example, a perfectly fluidized bed may suddenly agglomerate and defluidize if a liquid is slowly added to it and it exceeds a threshold limit. Excess moisture in a fluidized bed can make it difficult for particles to flow due to the surface tension of the liquid. If excessively wet biomass is fed into a fluidized bed, first the liquid droplets contact the bed particles in the feed zone and then they spread over the particle surface forming wet embryonic agglomerates due to liquid bridges. Thus defluidization could occur near the feed zone. As the liquid dries, bridge is broken, but if the liquid contains dissolved solids like in slurry fuels, the liquid bridges may be converted to solid bridges. If the binding strength of the solid bridges exceeds the break-up forces of fluidization, a size growth will occur. Following section presents a description of particle growth that could occur due to coating of particles or particles coming together through external forces (Mettanant et al., 2009).

Melt-induced agglomeration is caused by compositions of biomass ash that vary with its source and the growth conditions. However, inorganic components of a biomass are normally dominated by silicon, calcium and potassium and in some cases small amounts of aluminum (Lin et al., 2003). When the biomass is combusted at high temperatures, these components can react with the bed particles, typically sand, and form a eutectic mixture. This phenomenon is called "melt-induced" agglomeration because the bed material grains are "glued" together by a melt phase, see Figure 11. It can also be called heterogeneous agglomeration, because the formed particles are large and irregularly shaped (Mettanant et al., 2009).

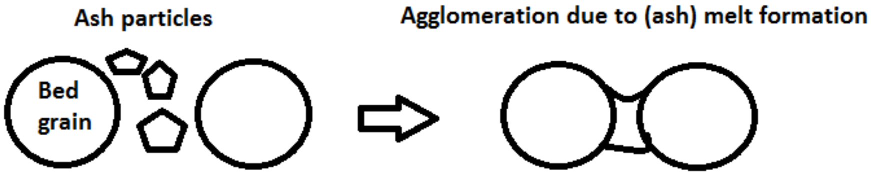

Figure 11. Melt-induced agglomeration.

Source: adjusted by author, according to Mettanant et al., 2009.

Coating-induced agglomeration is more common and is the dominant process in most commercial scale installations. Here, a coating or "onion-ring layering" (Saleh et al., 2003) is formed on the surface of the bed materials. The coating-induced agglomeration is also called heterogeneous agglomeration since the amounts of alkali and silicon that come from fuel ash or from additives are relatively low. Thus the sticky phase formed by their reaction is only able to cover the bed particles with a very thin layer. Scheme of coating-induced agglomeration is shown on Figure 12 (Mettanant et al., 2009).

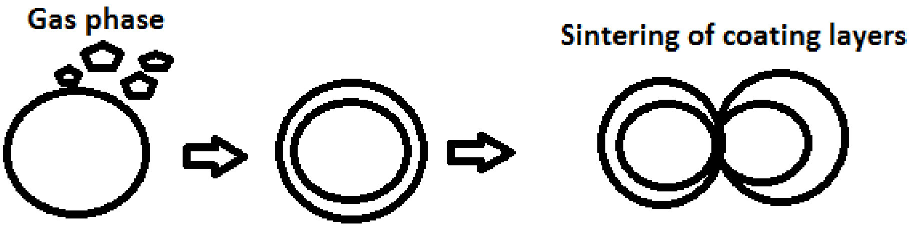

Figure 12. Coating-induced agglomeration.

Source: adjusted by author, according to Mettanant et al., 2009.

4.4.4. Pollutant emissions

Biomass combustion process is accompanied by the emission of many pollutants. Primary pollutants formed are particulate matter (PM), carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen (NOx, principally NO and NO2), and oxides of sulphur (SOx, principally as SO2). Acid gases, such as hydrochloric acid (HCl), may be emitted and also other heavy metals. CO and HC, including volatile organic compounds and polycyclic aromatic hydrocarbons (PAH), are products of incomplete combustion. These components are largely controlled by stoichiometry and proper fuel moisture control measurements (McKendry, 2002b). Practically, in any combustion conditions the emission indicators of total organic compounds are the lowest for coal combustion but for biofuels have attained higher values. Similarly to the former emission indicators and in the case of total organic compounds the highest value of emissions were obtained for straw and pellets but the lower ones for willow and bark. Initially, this indicator decreased and then it increased with the increase of temperature achieving the minimum at a level of 800-900 °C. This is a very unfavourable phenomenon because it is evidence that organic compounds are synthesized at elevated temperatures from organic radicals present in the combustion zone. These steps include cyclization, i.e. the creation and ring closure of aromatic compounds and also chlorination and dioxin synthesis. Gaseous chlorine is practically always present in the combustion zone because all fuels, including biomass, contain small quantities of chlorine. In the case of coal combustion, dioxin synthesis takes place at high temperatures and to a smaller extent due to the inhibitory influence of sulfur present in coal. In the biofuels the amount of sulfur is considerably lower and, therefore, emission of dioxins and furans may be expected (Lavric et al., 2005; Wielgosiński et al., 2016).

4.5. Solution of problems within biomass combustion

4.5.1 Preventing fouling and slagging

Slagging and fouling can lead to reducing heat transfer efficiency, also can damage superheaters and this factors can lead to unscheduled shutdown of combustion facility. As mentioned above, main factors responsible for slagging and fouling are alkali metals. The most important elements included K, Cl and SO_2 (Niu et al., 2016). In order to control a long – term ash deposition, it is necessary to discuss a cycle of the growth and drop of the ash deposition layers. This cycle frequency would be influenced by an adhesion force between ash deposition layer and the tube surface (Naganuma et al., 2013). According to Hare et al. (2010), Naganuma et al. (2013) and Niu et al. (2016) the ways to prevention of slagging and fouling as follows:

- Use of additives and/or use of alloys which prevent formation of deposition on a surface of superheater and other parts of combustion facilities
- Use of mechanism of soot blowers
- Use of anti-deposition coatings or use alloys that could prevent the destruction of combustion facilities

The most promising additives that can reduce slagging and fouling are mineral additives. Alkali compounds could by captured by clay minerals, especially kaolin. Addition of 10–20 µm kaolin makes up 2–3% by weight of the feed is more effective in reducing the ash problems (Hare et al., 2010). Niu et al. (2016) and Naganuma et al. (2013) discovered that relatively expensive kaolin could be replaced with soil which presents almost the same effect on ash fusion temperatures and served as additives during biomass combustion. Also, kaolin mixed with soil and SiO_2 is promising way to prevent the deposits. In comparison with pure biomass the additions of SiO_2, kaolin, and soil increase the ash fusion temperatures as a whole which considerably increase due to the formation of more high-temperature refractory materials from the additives directly and/or reactant products indirectly. Meanwhile, the additions of kaolin and soil present the almost same level increasing in the ash fusion temperatures. Whereas, further study on soil is need to be conducted because of the various compounds of the different soil sources.

Another way to prevent deposition is the use of mechanism of soot blowers. Soot blowers can be used to clean the heated surface of boilers during operation with a blowing medium of water or steam (compressed air). The blowing medium is directed on the deposit through a nozzle. That causes the deposit to crack and be eroded away. Mainly steam is used due to its ready availability as well as suitability to remove large accumulation while causing less thermal shock to the tubes. The application of soot blowers varies widely based on the quality of fuel, and range of boiler operating conditions. Two distinct types of soot blower are used, the long retractable soot blowers that extend a fair way in and clean the handing pendants such as the superheaters and the another type is short retractable shoot blower that extend a short way into the blower and release steam onto the tubes close by. The main disadvantage of this method in general is that a percentage removal of slag on the back side of tubes is very low (Hare et al., 2010).

The last solution is to use anti-deposition coatings or use alloys that could prevent the destruction of combustion facilities. Ceramic and non-catalytic anti – deposition coatings are used on the internal surfaces of the boilers. The coating is generally very dense having, being less than 1% porosity, and is able to significantly reduce the occurrence of molten ash particles sticking to the surfaces. It is also able to withstand severe thermal cycling that occurs when boiler loads are changed and when hydro jets are in use. Coatings have limited effectiveness in some areas of the boilers especially upper slopes and the wing-wall tubes. On the lower angle slopes of the upper walls specific gas flow patterns sometimes render the coatings ineffective while the small gaps that are sometimes present in the wing wall designs allow slag to bond itself between the tubes (Hare et al., 2010). Naganuma et al. (2013) investigated the deposition of biomass ash in relation to metal alloys. These parameters were evaluated at high temperature for a long period using the high precision tension tester. The results lead to the conclusion that the adhesion force depend on the metal specimens. Ni-alloys coated by thermal spraying technique, in particular, reduce the adhesion of ash deposits on segments of combustion facilities.

4.5.2 Preventing corrosion

The corrosion rates of the superheater in a boiler can be reduced by keeping steam temperature low. However, this results in poor electrical efficiency. The steam parameters can be maintained at high temperature and pressure if the high temperature corrosion is prevented. The strategies to prevent high temperature corrosion according to Demirbas (2005), Saidur et al. (2011), Karlsson et al. (2015) and Raja & Elayaperumal (2015) are:

- Use of additives
- Co-combustion of biomass and coal or municipal sewage sludge
- Use of more advance superheater materials or higher cast irons superheater materials

Studies suggest the use of different materials such as bauxite, kaolinite, limestone and magnesium oxide and other additives to produce high melting point alkali compounds relative to alkali chlorides. These additives are meant to increase the melting point of the ash formed during combustion. By application of the majority of these materials, chlorine is released in gas phase, thus not totally eliminating the corrosion effect (Saidur et al., 2011). The additives have mainly impact on increasing the availability of sulfur (in the form of SO_2 and/or SO_3) in the boiler. This includes sulfur-based additives such as elemental sulfur, ammonium sulfate and sulfur recirculation. Laboratory studies have shown that the presence of potassium sulfate induces no accelerated corrosion attack on stainless steel at 600 °C. The non-corrosive nature of potassium sulfate at this temperature is explained by its reluctance to react with the protective chrome surface of the superheater in a boiler (Karlsson et al., 2015).

To reduce corrosion can be used either co-combustion of biomass and coal or municipal sewage sludge (Demirbas, 2005; Karlsson et al., 2015). The mechanism to prevent corrosion by co-combustion of biomass with coal is that the amount of chlorine in the deposit decreases sharply with increasing sulphur content, and that cofiring a high-chlorine, low-sulphur biomass fuel with a sulphur-containing coal often results in deposits with very low chlorine thereby reducing the occurrence of corrosion (Demirbas, 2005). Co-combustion of biomass with municipal sewage sludge has the same aim of using as the co-combustion with coal – to sulphate alkali chlorides into their corresponding sulphates during the simultaneous release of hydrogen chloride or chlorine (Karlsson et al., 2015).

Another way to prevent corrosion is to use cast irons. There are several types of cast irons, exhibiting different mechanical properties and microstructures (white cast iron, malleable cast iron, etc.). Un-alloyed cast irons are normally applied. However, they can also be alloyed in order to enhance corrosion resistance. Silicon, nickel, chromium, copper, and molybdenum have been found to improve the corrosion resistance of cast irons. High silicon cast iron (12-18%) has been known to exhibit excellent erosion corrosion resistance (Raja & Elayaperumal, 2015).

4.5.3 Preventing agglomeration

According to Mettanant et al. (2009) there are four ways to avoid formation of agglomeration:

- Use alternative bed materials which do not agglomerate at operating bed temperatures
- Add additives to bind volatilized alkali before it reacts with silica to initiate agglomerates
- Reduce concentration of agglomeration causing elements in fuel by pretreatment or cofiring other fuels
- Reduce operating bed temperatures

Physical and chemical properties of bed materials have a major effect on agglomeration. Use of alternative bed materials or additives is considered for reduction of agglomeration and it is the most attractive remedy due to its simplicity and low cost. Several alternative materials are proposed instead of common silica (or sand) for use as bed materials. Suitable materials to avoid agglomeration are dolomite, limestone, alumina, feldspar (a major component of Earth's crust), ferric oxide and magnesite (Saidur et al., 2011; Mettanant et al., 2009). Use of alumina was one of the first interventions against agglomeration, where the element is used instead or mixed with silica sand because it is suitable sorbent for gaseous alkali (Saxena & Rao, 1993; Mettanant et al., 2009). Replacing of silica bed material with lime and dolomite is effective in reducing sintering. Combustions tests with limestone as bed material have largely eliminated ash agglomeration in the bed, and reduced the ash sintering in the deposits on downstream heat exchanger tubes, but it experienced agglomeration when run with sand bed under the same operational conditions (Mettanant et al., 2009). Good behavior of limestone bed materials compared with the silica bed material is due to the dilution effect which is caused by adsorption of alkaline salts on the surface of lime and portlandite, which are more porous than limestone (Angew et al., 2000). The limestone bed material acted as a sink of lignocellulosic biomass ash and its elements, even with elements considered to be volatiles. Limestone also reduced agglomeration potential by increasing the initial agglomeration temperature in fluidized – bed combustor. The limestone in the bed calcined to lime at the operating temperature. Use of magnesite to avoid agglomeration works on the same principle as use of alumina (Mettanant et al., 2009).

Additives are the substances used to alter the physical and/or chemical properties of fuel. Generally additives are used to increase the melting temperature of ash during the combustion of biomass. They decrease agglomeration as well as corrosion, fouling and slagging; while potentially reduce emissions of CO, hydrocarbons, particulates, NO_x, and SO_2. Materials that can be used as additives are kaolin, dolomite, limestone, and calcium oxide thus preventing reactions between silica and potassium phosphate (Saidur et al., 2011; Mettanant et al., 2009). All additives works on the same principle, for example by adding kaolin and dolomite with the fuel, the initial bed agglomeration temperature increased from 830 to 890°C and 905°C respectively, so kaolin increase bed temperature and thereby prevents the agglomeration (Ohman et al., 2003).

Not all of alternative bed materials and additives have only advantages, some of them namely dolomite, magnesite, ferric oxide, alumina, feldspar, and aluminum rich minerals have been proposed and tested with range of problems. Problems associated with the proposed materials include high attrition and entrainment rates, chemical stability, and other problems (namely windbox and air nozzle plugging). Here it can be seen that the additives which may be very useful in the reduction of agglomeration may also damage the combustion device in other way (Saidur et al., 2011).

Another way to prevent agglomeration is co - combustion of biomass with other fuels such as coal that can reduce the concentration of potassium or sodium in ash because kaolinite and other aluminosilicates in coals act as sorbents. They flux agglomerating elements from the biomass and delays the time of occurrence for agglomeration and it also has a very limited window of operation (Mettanant et al., 2009; Saidur et al., 2011). Werther et al. (2000) suggested that mixing biomass with small amounts of fossil fuels reduces the agglomeration problem but the fossil fuels used should have high ash content. The hypothesis was tested by blending coffee husks with 20% coal, which have 40% ash. The potassium concentration in the resulting ash reduced from 43.8% to 13.5% (Werther et al., 2000).

One of the other ways to prevent agglomeration is high initial agglomeration temperature if such an option is available. Bed temperature affects the melting of ash that covers the bed particles, which affects the agglomeration. The initial bed agglomeration temperature depends on the concentrations of potassium and calcium in fuel. Fuel with low potassium and high calcium contents will have a high melting temperature. Bark, cane and wood residue are all examples of this. On the other hand, fuels will have a lower agglomeration temperature if it has high potassium and low calcium, such as wheat straw and wood (Mettanant et al., 2009).

The last method to prevent agglomeration is pre-treatment of biomass fuel. Experiments on the effect of bed particle size on agglomeration (Saleh et al., 2003; Chirone et al., 2006) indicated that sand size has a pronounced effect on agglomeration. Increasing the size of the bed particles could decrease the bed agglomeration, as larger bed particles have greater inertia and they have more energetic collisions.

Consequently, adhesion of the particles to each other to form agglomerates should be more difficult. The results of Chirone et al. (2006) showed that large sand particles (600–850 µm) take longer (approximately twice as long) to get defluidized than the small sand particles (212–400 µm). Saleh et al. (2003) suggested that 30% addition of coarse particles was the optimum ratio to avoid agglomeration (Mettanant et al., 2009).

4.5.4 Preventing pollutant emissions

Prevention of pollutant emissions is follows in accordance with Juszczak & Lossy (2012) and Abuelnour et al. (2014)

- Use of primarily wood material for combustion
- Use of advanced combustion technology

Juszczak & Lossy (2012) noticed a positive influence on the combustion process when adding wood materials to agricultural residues, namely in a mixture of vine shoots and industrial cork residue in form of pellets. The best results were obtained with a fuel mixture composition of 30 wt % vine shoots and 70 wt % industrial cork residue, in which case carbon monoxide concentration was 1700 mg/m^3 (presented for 10% O2 content in flue gas). For comparison purposes, it is worth indicating that carbon monoxide concentration while firing cork residue pellets or vine shoots alone was higher (3100 and 9000 mg/m^3, respectively). Similar conclusions were drawn for combining tomato residues, olive stones and cardoon with wood pellets. The lowest carbon monoxide concentration was obtained for the following mixtures: tomato residues/wood (75/25 wt %), tomato residues/olive stones (50/50 wt %), cardoon/wood (50/50 wt %), olive stones/wood (25/75 wt %). In general terms, the higher the proportion of wood pellets in the mixture, the lower carbon monoxide concentration in the flue gas.

Another possibility is to use advanced combustion technologies for example flameless combustion, as mentioned above, where due to high temperature and preheated air, the fuel is completely burn. This technology reduces NO_x emission to zero and another pollutant emission near to zero (Abuelnour et al., 2014).

5. Conclusion

Combustion of solid biofuels is an ecological way to generate energy. During combustion of solid fuels from biomass are arising certain aspects that need to be addressed in order to get an efficient fuel, e.g. moisture, ash content, content of volatiles, calorific value and ignition time.

The combustion process takes place in boilers with different technologies such as for example fixed-bed boilers. This technology, made primarily for coal combustion, has been the most used for burning biomass-based biofuels for many years. Its benefits include quite high efficiency and the possibility to use biofuels with high ash content. Disadvantages incorporate high amount of deposits adhering to the surface of the boiler, unacceptability to use of larger and non-uniform pieces of biofuel, and necessity of the combustion chamber's modification for the combustion of biofuels.

The second available technology is combustion in fluidized-bed boilers, where the material is combusted in sand or other non-flammable material and maintained in a turbulent suspension. This technology has been evaluated as the best available for combustion of biofuels due to its benefits, including high fuel tolerance, high efficiency through the maintenance of moving parts of the material and thus improved combustion. The disadvantage is the ash agglomeration and the amount of dust in the gas phase.

Biomass can also be co-combusted with coal, where the big advantage is greater efficiency thanks to the use of fossil fuel and reduction of aggressive chlorine oxides. However, the disadvantage is that the proportion of biofuel used is usually limited and the cost increase relative to the transport and production of biofuels.

Additionally, there are advanced technologies like flameless combustion that reminds pyrolysis. Combustion takes place at high temperatures with low air access. The biggest advantage is the reduction of polluting emissions, especially NO_x. The disadvantage is the fuel flashback and poor combustion stability.

Combustion of biofuels also face problems associated with their chemical composition. First of them are slagging and fouling caused by ash collected on the surface of boiler.

This problem can be prevented by the use of additives, soot blowers technology or application of anti-deposition materials for boiler's manufacturing.

The second problem is corrosion caused by moisture, aggressive chlorine oxides or as a result of slagging and fouling. Its prevention and minimization is possible in three main ways by adding additives, co-combustion with coal and using anticorrosive alloys for boiler production.

Another common problem is the ash agglomeration, which involves combustion in fluidized-bed boilers. At higher temperatures it occurs melting of the chemical elements contained in the biomass as well as successive sintering with the sand or other fluid-bed material, which causes defluidization of the facility. Preventing and minimizing has following options: use of alternative bed materials or additives, co-combustion of biofuels with coal, pretreatment of biofuels and temperature reduction.

The last mentioned problem is the pollutant emissions resulting from the release of volatile content during combustion process. This problem can be minimized by using mainly wood fuels or by applying advanced technologies such as flameless combustion.

Combustion of solid biofuels is a suitable way to obtain energy. Scientific research and manufactures are focused on improving existing technologies for combustion of biofuels in order to get greater efficiency. In addition, combustion problems should be taken into consideration within the boiler production/design and biofuel preparation itself.

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