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Research article

Deposit build-up and ash behavior in dual fluid bed steam gasification of logging residues in an industrial power plant

Matthias Kuba [a,*], Hanbing He [c], Friedrich Kirnbauer [a], Dan Boström [d], Marcus Öhman [c], Hermann Hofbauer [b]

[a] Bioenergy 2020 + GmbH, Wiener Straße 49, A-7540 Güssing, Austria
[b] Vienna University of Technology, Institute of Chemical Engineering, Getreidemarkt 9/166, 1060 Vienna, Austria
[c] Luleå University of Technology, Energy Engineering, Division of Energy Science, SE-971 87 Luleå, Sweden
[d] Umeå University, Energy Technology and Thermal Process Chemistry, SE-901 87 Umeå, Sweden

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ABSTRACT

A promising way to substitute fossil fuels for production of electricity, heat, fuels for transportation and synthetic chemicals is biomass steam gasification in a dual fluidized bed (DFB). Using lower-cost feedstock, such as logging residues, instead of stemwood, improves the economic operation. In Senden, near Ulm in Germany, the first plant using logging residues is successfully operated by Stadtwerke Ulm. The major difficulties are slagging and deposit build-up. This paper characterizes inorganic components of ash forming matter and draws conclusions regarding mechanisms of deposit build-up. Olivine is used as bed material. Impurities, e.g., quartz, brought into the fluidized bed with the feedstock play a critical role. Interaction with biomass ash leads to formation of potassium silicates, decreasing the melting temperature. Recirculation of coarse ash back into combustion leads to enrichment of critical fragments. Improving the management of inorganic streams and controlling temperature levels is essential for operation with logging residues.

1. Introduction

A steadily rising CO_2 concentration in the atmosphere, which is linked to climate change, has increased the demand for the development of multiple technologies using renewable energy sources. Using solid biomass as a resource is one way to raise the ratio of renewable energy in our energy system. As a CO_2-neutral carbon source it is suited for usage in pyrolysis, gasification and combustion systems. Steam gasification of biomass is a promising technology for generating electricity and heat as well as synthetic products such as bio-fuels or chemicals. A dual fluidized bed (DFB) steam gasification process was developed at the Vienna University of Technology which is able to produce a product gas that can be further used to generate electricity, heat, fuels for transportation and synthetic chemicals. Thanks to the flexibility of the technology it can quickly adapt to changes in the energy market.

The principle underpinning this process is the separation of endothermic gasification and exothermic combustion. Heat which is necessary for gasification is provided by a circulating bed material from the combustion to the gasification zone. Steam is used as fluidizing agent for the bubbling bed in the gasification zone. Fast fluidization in the combustion zone is realized by using air. Part of the biomass is combusted to provide the heat necessary for gasification [1–4]. Since 2001 the process has been successfully demonstrated at the biomass power plant in Güssing, Austria, which has a fuel power of 8 MW_{th}. In Oberwart, Austria, a biomass power plant with fuel power of 8.5 MW_{th} has been in operation since 2007. At Senden, near Ulm in Germany, a plant with fuel power of 15 MW_{th} has been in operation since 2011. Next generation dual fluid bed gasification is currently investigated at the Vienna University of Technology [5–7].

In contrast with all other gasification power plants the Senden plant is operated with logging residues together with wood chips as feedstock. As regards this lower-cost biomass, the major difficulties of operation are deposit build-up and slagging. Avoiding build-up of deposits may increase the availability and consequently the operation time further and is therefore important as regards the optimization of the plant. Previous studies showed an interaction between bed particles and ash during combustion of biomass feedstock. As a consequence of this interference calcium-rich layers are built around bed particles [8–10]. Investigations of time dependence regarding layer formation on quartz sand particles from a 30 MW_{th} bubbling fluidized bed biomass combustion plant showed several steps of layer growth. On the first day of operation only one thin Ca-, Si- and K-rich homogeneous layer with a relatively high K/Ca molar ratio could be observed. Particles aged one day to two weeks also showed an outer Ca-rich layer. During the initial phase of layer formation, the growth rate was relatively high, but decreased over time [11].

A correlation between bed particle layer formation and bed agglomeration has been established, mainly focusing on combustion of wood fuels [8,9,12–15]. Since layers on particles originate from biomass ash,

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[*] Corresponding author.
E-mail address: matthias.kuba@bioenergy2020.eu (M. Kuba).

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they have a high probability of melting in zones of elevated temperatures. Partly melted layers act as glue and cause particles to stick together [16–18]. Biomass ash leading to deposits has been investigated in the past for biomass combustion systems [19–23]. Depositions found in circulated fluidized bed combustion of woody biomass consisted mainly of bed particles embedded in a homogeneous melt. Potassium species from the feedstock interact with quartz sand bed particles to form sticky alkali-rich silicates. These sticky silicate melts can adhere to the walls of the cyclone or the return legs. Ordinary bed particles can deposit on the surface of those melts [24]. Impurities such as quartz and feldspar further enhance slag formation [25–27].

Similar findings can be observed for dual fluid bed gasification of biomass. During long-term operation of the biomass DFB gasification plant in Güssing two calcium-rich layers formed on the bed material. The inner layer mainly consisted of calcium silicates and the outer layer had a composition similar to fine ash. The formation of calcium-rich layers is owed to the high calcium content of the woody feedstock and addition of calcium-rich additives to the reactor. This formation may arise from intensive contact with burning char particles. Molten ash components stick on the surface and calcium diffuses into the particles. The smooth surface of the layer indicates that the formation occurs with a molten surface [28]. Layers on olivine have a positive catalytic influence in the gasification process. They increase its catalytic activity enhancement of gasification reactions and reduce tar dramatically. Measurements at the biomass gasification reactor at the Vienna University of Technology showed a significant decrease of tars when layered olivine was used [29,30]. The water–gas-shift reaction is enhanced, which leads to higher hydrogen and carbon dioxide content in the product gas [31].

This paper focuses on the characterization of inorganic compounds in dual fluid bed biomass gasification of logging residues. X-ray fluorescence (XRF) analysis of different ash fractions in the systems was conducted. Results from these analyses were compared with other investigations with an environmental scanning electron microscope (ESEM) and X-ray diffraction (XRD). As a result, tracking of critical components regarding deposit built-up could be realized. Chemical equilibrium calculations were performed to evaluate melting behavior of compounds appertaining to slagging phenomena. Particle size fractionation enhanced knowledge of particle pathways in the system. Therefore, critical compounds could be assigned to certain parts of the reactor set-up. From the results of these analyses conclusions regarding the mechanisms of deposit build-up in the combustion area of the DFB system are drawn.

2. Materials and methods

2.1. Description of the industrial biomass DFB gasification plant

Samples for investigation were taken from the biomass combined heat and power (CHP) plant in Senden, Germany. It has fuel power of 15 MW_{th}, generates electricity of about 5.1 MW_{el} in two gas engines and an organic rankine cycle (ORC) and also produces district heating of about 6.4 MW_{th}. Logging residues, including cut-off root ends, tops, and branches, are used as feedstock. This lower-cost feedstock comprises on average 15% of bark and 15% of needles; therefore, only 70% of the used fuel is wood chips. Because of decentered chipping, mainly by the forest industry, the particle size distribution and water content vary considerably. The feedstock is collected in four storage silos before it is fed into the biomass dryer. Hence, a good fuel mixing can be achieved before the feedstock is put into the gasifier. The specifications mentioned above are constantly monitored by a feedstock management process executed by the staff of the power plant on site.

Fig. 1 shows a flow sheet of the power plant. Feedstock enters the gasification reactor via a screw conveyor, where the biomass is led directly into the bubbling fluidized bed. Therefore, gases released from the biomass are immediately in contact with catalytically active bed material. Olivine is used as bed material. It has two major roles in the process. First, it acts as a circulating heat carrier between the combustion reactor and the gasifier. Second, it performs as a catalyst regarding the decomposition of tars. The bubbling bed is kept at a temperature of around 850 °C and steam is used as a gasifying agent. Calcite is brought into the system as an additive to enhance the catalytic activity of the olivine. Bed material is transported together with char from the solid feedstock from the gasifier into the combustion reactor via a chute. In this zone air is used for fluidization and full oxidation is achieved. As a result, bed material particles are heated up and temperatures of up to 950 °C are reached. After it has been transported through the fast fluidized combustion reactor the bed material enters a cyclone which separates the bed material from flue gas. Small particles which are not separated from the gas stream by the cyclone enter the post-combustion chamber. Air is added at the inlet of the chamber to secure complete oxidation of flue gas. Since the post-combustion chamber is widened after the inlet, the gas stream is slowed down and further redirected by 180° before leaving the chamber. The gas stream is then led through a radiation channel where the temperature of the flue gas is cooled down to about 630 °C. Particles in the gas stream are again divided by a gravitational separation unit. Bigger particles are recirculated back into the combustion reactor and are referred to as coarse ash. Smaller particles are dragged to a flue gas filter by the gas stream and are collected as fine ash. This fine ash is finally removed from the system.

Small biomass particles which are entrained out of the gasifier together with the product gas stream are referred to as fly coke. The product gas is cooled down by heat exchangers before passing through a product gas filter, where fly coke is separated. Impurities in the product gas which cannot be separated by the filter, such as tars, ammonia or sulfur components, are captured in a product gas scrubber filled with methyl ester of rapeseed (RME). Collected fly coke is transported back into the combustion reactor, since it still contains combustible compounds. The cleaned product gas is utilized in gas engines to generate electricity and heat. A small amount of product gas is brought back to control the temperature of the combustion zone. Used, layered olivine is periodically replaced by fresh olivine to make up bed material losses owed to attrition. Therefore used (aged) olivine is let out of the combustion reactor at the bottom and fresh olivine enters together with coarse ash and fly coke.

2.2. Sampling

Sampling was conducted during and after two different operation periods. On both occasions the power plant was continuously operated for around 1200 h without cooling off. Fig. 1 shows the sampling locations in the power plant. Deposition samples were taken out of the post-combustion chamber on two different dates during the shutdown of the power plant after the operation periods. On each of the dates samples from three different positions were collected. From each position two samples were investigated. Thus, a total of 12 deposition samples were analyzed. Samples of bed material, coarse ash, fine ash, fly coke and feedstock were taken during the corresponding operation periods of the power plant which led to the build-up of the deposits. To obtain representative values samples from two different days of the operation period were collected. Sampling of bed material, coarse ash, fine ash and fly coke was conducted during steady-state operation. Bed material samples were collected at the bottom of the combustion reactor. Samples of coarse ash and fine ash were both taken after the gravitational separation of the two ash streams. The sampling point of the coarse ash was located below the gravitational separation chamber and that of the fine ash at the flue gas filter. Fly coke was collected from the product gas filter. Biomass feedstock was taken for every delivery at the power plant over a day. In total, eight trucks delivered the wood chips to the plant each day. A sample corresponding to the amount of biomass