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Co-firing of agricultural fuels in a full-scale fluidized bed boiler

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ABSTRACT

An experimental campaign was carried out at a power plant to specify the challenges related to fluidized bed combustion of agricultural fuels and demonstrate a technically viable concept for establishing a 20% share of agricultural fuel co-fired with woody biomass. Sunflower seed hull pellets and oat seeds (unsuitable for food purposes) were co-fired with wood chips. The share of agricultural biomass varied, reaching up to 30%, on a received mass basis. Deposit probes, gas and solid samplings by a Dekati low-pressure mass impactor (DLPI) and an electrical low-pressure impactor (ELPI), and a Fourier transform infrared (FTIR) analyzer were utilized to monitor the risk of high-temperature corrosion, slagging, and fouling. Fluidized bed behavior was monitored by taking samples directly from the bed.

High-temperature fine-particle sampling was successfully applied for high-potassium and high-phosphorus fuels. Formation of potassium silicate was shown to have the main role in the furnace-wall slagging process. The technical concept of combustion of agricultural fuels by bubbling fluidized bed technology was successfully demonstrated and established. It includes operation below 750 °C bed temperature and ensuring furnace-wall cleaning by means of in-furnace water cannons. The high-temperature corrosion risk can be mitigated by sulfur addition.

1. Introduction

There is strong political consensus in Europe for increasing the share of renewable fuels in heat and power production, to slow down anthropogenic global warming. At the same time, there is concern about the overuse of forests. Agricultural biomass residues from food production and energy crops have been seen as an option. In Poland, the Energy Law specifies a "green certificate" system for implementing the European Union's directive on electricity purchased from renewable sources (2001/77/EC). That requires increasing the contribution of energy crops or other material of agricultural origin; these must account for at least 20% of electricity production (by wet mass) at the end of 2012. The proportion then will be gradually increased until 2017.

The properties of agro fuels entail many challenges for the combustion process. Nitrogen, phosphorous, potassium, magnesium, and chlorine content are usually higher in comparison to woody biomass, due to the use of fertilizers. Potassium and chlorine vaporize easily and are known to have an important role in bed agglomeration, fouling, slagging, and high-temperature-corrosion-related processes. Phosphorus takes part in bed-agglomeration-, fouling-, and slagging-related phenomena. An increase in nitrogen content may elevate NO_x emissions.

Sintering of bed particles in fluidized bed boilers may proceed by at least three mechanisms: partial melting, viscous flow sintering, and solid–gas-phase chemical reactions [1]. Alkalis play a key role in all these mechanisms. The sand typically used as bed material in fluidized bed boilers contains 25–100% quartz by weight [2], and quartz tends to form low-melting-point alkali calcium silicates with ash of alkali-rich fuels [2–7]. These compounds coat bed particles and eventually bind them to agglomerations [2–7]. Both additives [7] and quartz-free bed materials [2–5] have been experimentally studied at laboratory scale to control bed agglomeration. Blast furnace slag [3] and diabase [2] have been used at full-scale fluidized bed boilers. Bed agglomeration may occur for physical reasons too. Coarse unfluidizable material, such as gravel, glass, and pieces of metal, may disturb fluidization to such an extent that combusting fuel and char particles will increase the temperature locally above the initial deformation temperature of quartz sand particles. In practice, both chemical and physical reasons arise simultaneously.

The alkali chlorides vaporize at fluidized bed combustion temperatures and come into contact with the heat transfer surfaces by direct condensation or through thermophoresis [8]. Alkali chloride plays a significant role in initiating the high-temperature corrosion process. These chlorides lower the first melting point of the deposit and thus introduce the possibility of molten-phase corrosion. However, the presence of alkali chlorides in the deposit has caused accelerated corrosion well below the melting point of KCl [9–11].

The conventional ways to control high-temperature corrosion are via boiler design (i.e., superheater arrangement) and through the selection of materials. The individual superheater section can be put in a less corrosive environment, as in final superheater placement at the loopseal of a circulating fluidized bed boiler. Or the steam flow

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direction (counter-currently or co-currently) in individual superheater sections can be optimized in relation to flue gas flow. The threshold material temperature for alkali-chloride-induced superheater corrosion is 450 °C [9]. With high-chlorine fuels, below that temperature, low alloy steels, such as 10CrMo9-10, can be used. Above 450 °C, high-chromium alloys, like TP310HCbN, with a Cr content higher than 25% are preferred [9].

The superheater corrosion risk of high-alkali and high-chlorine fuels can be reduced also by changing the flue gas atmosphere through co-firing with coal [13,17–19], peat [18,26], and sludge [20] or with sulfur, sulfate, or aluminum silicate containing additives such as elementary sulfur [21,22], ferric sulfate ($Fe_2(SO_4)_3$) [25], aluminum sulfate ($Al_2(SO_4)_3$) [25], ammonium sulfate ($(NH_4)_2SO_4$) [22–24,26], and china clay ($Al_2O_3 \cdot SiO_2 \cdot H_2O$) [20]. In the case of co-firing with coal or sludge, sulfur and aluminum silicates simultaneously prevent alkali chloride formation. With peat, the sulfur sulfates the alkali chlorides. Alkali in alkali chlorides can be sulfated by $SO_{2(g)}$ and $SO_{3(g)}$ [9–26], from which HCl is liberated. The overall sulfation reaction is as follows:

$$2MCl_{(g,c)} + SO_{2(g)} + {}^{1}/{}_{2}O_{2(g)} + H_2O_{(g)} \rightarrow M_2SO_{4(g,c)} + 2HCl_{(g)} \qquad (1)$$

where M is Na or K.

Naturally, a few percent of the $SO_{2(g)}$ formed may further react to create $SO_{3(g)}$. In the combustion environment, this takes place thermally at high temperatures (>1100 °C) or by catalyzed reactions at lower temperatures (500–800 °C). Among such catalysts are iron oxide and vanadium oxide. Iron is quite a common element in coal ash and vanadium in heavy fuel oil. Both $SO_{2(g)}$ and $SO_{3(g)}$ are able to sulfate chlorides, but the speed of reaction for $SO_{3(g)}$ is of a much higher magnitude [12–16].

The advantageous ability of $SO_{3(g)}$ to sulfate alkali chlorides more effectively than $SO_{2(g)}$ is studied and demonstrated at laboratory scale [25] and in industrial boilers [22–24,26]. Krause [11] suggests that a fuel S/Cl molar ratio of at least 4 is enough to achieve negligible chlorine deposition on superheaters when refuse-derived fuels are fired. Salmenoja [9] proposes that the tendency for corrosion is high with biofuels if the fuel's S/Cl molar ratio is below 2, moderate if that molar ratio is between 2 and 4, and low when the ratio is above 4.

The target of the full-scale experiment was to specify the challenges related to fluidized bed combustion of agricultural fuels and demonstrate a technically viable concept for establishing a 20% share of agricultural fuel co-fired with woody biomass. The question for the power plant operator is always the same: How much of a new fuel can I add safely without compromising plant availability or exceeding the emission level limits? What kind of mechanical or control software changes are needed? A comprehensive combustibility evaluation should include review of the risk of bed agglomeration, fouling, high-temperature corrosion, effect on flue gas emissions, and ash quality (reuse or landfilling). This paper concentrates on bed agglomeration, fouling, slagging, and high-temperature corrosion.

2. Material and methods

2.1. Description of the plant

The demonstration was carried out at Elektrociepłownia Białystok S.A's bubbling fluidized bed (BFB) boiler (138 bar, 540 °C, 29 kg/s, 75 MW_{th}) in Poland. Pulverized-brown-coal-fired boiler No.5 (OP 140) had been converted to biomass-fired BFB operation by Metso Power in 2008. Steam parameters were kept at the original level, with the exception of a decrease of steam flow from 140 to 105 t/h. The annual fuel consumption is approximately 230,000 t. The retrofitted plant was designed to utilize wood-based biomass with, at maximum, five percent agro fuels by weight. The furnace dimensions ($W \times D \times H$) are 6.1 m × 6.9 m × 22.9 m. The depth of the flue gas path, where the samplings and measurements were conducted (nearby secondary superheater and in the back pass), is 6.1 m.

The experimental campaign was carried out in three periods: pre-test, tuning, and measurement. During the six-week pre-test and tuning periods, the fuel feeding and boiler were prepared for high-agro-fuel-share operation. The measurement period reported upon here lasted 10 days, in total. Sampling and measurement connections, as well as the location of additive feeding, are presented in Fig. 1. Most of the connections are on the right-hand side of the boiler. Slag sampling by slagging probe was done from the front wall through connection 5.

2.2. Fuels

Two types of agro fuels, grain waste (oat seed) and sunflower husk pellets were co-fired with wood fuel. The Polish wood fuel contained both stem wood and logging residue types of fractions (bark and branches), in varying proportions. Each fuel type was sampled from the fuel yard prior to mixing. During each test, fuel blends were sampled every half hour from the conveyor just before the furnace. A composite sample was formed for each test. This was done because of the variation in fuel mixing at the fuel yard and the natural changes in quality of each fuel stream. For example, the properties of wood fuel vary in terms of their silicon, aluminum, and ash content. That is most probably due to soil contamination during fuel processing. The share of agricultural biomass ranges from 0% to 30% on an as-received mass basis. Agro fuel was combusted for 24 h continuously for several days. Each test lasts 2–3 h. Prior to measurement, there was a 2–4-hour stabilization period. For a change of fuel type or ratio, the stabilization period was at least 12 h. The tests conducted and the results of analysis of fuels and blends are presented in Table 1.

The ash content of agro fuels is slightly higher than that of wood fuel. In terms of ash composition, grain waste and sunflower husk pellets differ from wood in their higher phosphorus and potassium content. In comparison to wood fuel, chlorine levels are elevated in both of the agro

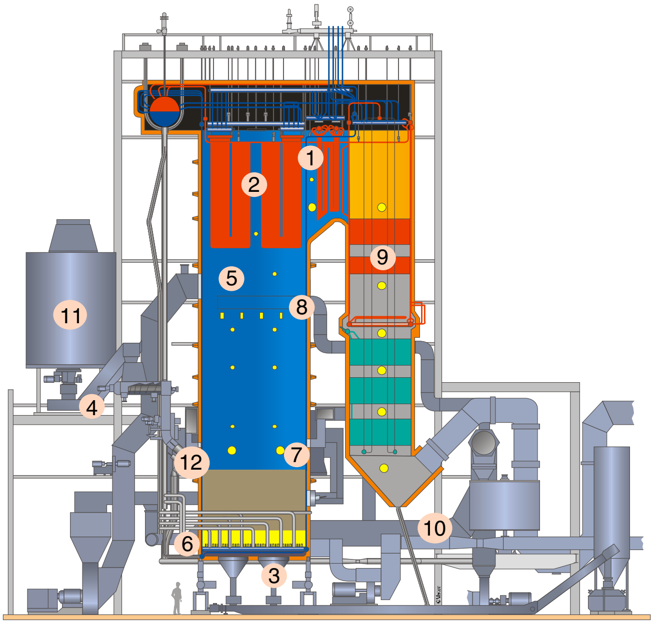

Fig. 1. The schematic diagram of the 75 MW_{th} BFB boiler. (1) Aerosol sampling, by Dekati low-pressure mass impactor (DLPI) and an electrical low-pressure impactor (ELPI), and a Fourier transform infrared (FTIR); (2) deposit sampling probe; (3) bed material sampling; (4) sulfur feed; (5) slag sampling probe at the front wall; (6) primary air inlet; (7) secondary air inlet; (8) tertiary air inlet; (9) flue gas composition measurement by FTIR; (10) flue gas recirculation gas duct to the primary air plenum; (11) fuel feeding silo; (12) fuel feeding chute.