



## Full Length Article

# Co-firing high ratio of woody biomass with coal in a 150-MW class pulverized coal boiler: Properties of the initial deposits and their effect on tube corrosion



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## HIGHLIGHTS

- The demo test of co-firing of high ratio biomass in a PC boiler was conducted in Japan.
- Initial deposits collected from furnace wall and superheater during the test were analyzed.
- Lab-scale corrosion tests was then conducted based on the properties of initial deposits.
- Co-firing increased locally corrosion rate of furnace wall boiler tubes.
- Co-firing did not affect corrosion rate of superheater tubes.

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## ABSTRACT

A demonstration test on the co-firing of a high-ratio of woody biomass (25% energy basis) with coal in a 150-MW class pulverized-coal boiler was conducted in Japan for the first time. To investigate the effect of the co-firing on the corrosion of the boiler heat-transfer tubes inside furnace wall and superheater, we collected the initial layer of the ash deposits (initial deposits) by inserting water-air-cooled probe simulating heat-transfer tubes during the test. Based on the results of the analysis of the collected initial deposits, we then prepared synthetic deposits and used them to conduct high-temperature laboratory-scale corrosion test for 500 h. Carbon steel (STB410) and low-alloy steel (STBA22) were used to represent the furnace wall tubes, while two austenitic stainless steels (Ka-SUS304J1HTB and Ka-SUS310J1TB) were used to represent the superheater tubes. The co-firing was found to produce deposits in the furnace wall containing twice as much sulfates (mainly  $\text{Na}_2\text{SO}_4$ ) compared to coal firing. A relatively high ratio of unburned carbon was also observed in the initial deposits of co-firing, indicating a strongly reducing atmosphere in the furnace wall. We found that the co-firing produced a higher corrosion rate in the furnace wall tubes at 500 °C compared to coal firing. The corrosion risk, however, can be mitigated by decreasing the reduction capacity of the atmosphere. Further, the co-firing was found to produce two to three times as much alkali sulfate, but nearly the same low level of unburned carbon in the initial deposits obtained in superheater compared to coal firing. However, the increased sulfates concentration in the deposits had negligible effect on the corrosion of austenitic stainless steel tubes in the oxidizing atmosphere of the superheater at 650 °C.

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## 1. Introduction

Japan has the ambitious target of reducing its total greenhouse gas emission to 26% of the 2013 level and increasing the ratio of electricity generated from renewable energy to the total electricity generation to 22%–24% by 2030 [1,2]. Owing to the introduction of

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the feed-in tariff (FIT) scheme for renewable energy in 2012, there has been a significant increase in the electric power produced from renewable energy sources in the country. However, this has been dominated by the exploitation of solar power, which accounts for 90% of new renewable energy installations [2]. The Japanese government thus aims to accelerate the utilization of other renewable energy resources that are independent of weather conditions, such as biomass.

Compared to pure biomass-firing, the co-firing of biomass with coal offers a more attractive method for generating electricity from biomass. It can be implemented using the extensive existing infrastructure of fossil fuel-based power plants, and requires relatively modest additional capital investment [3]. Moreover, it affords a higher conversion efficiency [4] and minimizes the ash-related problems such as fouling and corrosion compared to pure biomass firing [5]. It is also characterized by reduced SO<sub>x</sub>, NO<sub>x</sub> and greenhouse gas (CO<sub>2</sub>) emission compared to fossil-fuel power generation [6,7].

Although the co-firing technology of biomass with coal has been implemented in several coal-fired power plants in Japan, the biomass ratio in the country has been low, being <3% on energy basis [8]. To maximize the reduction of greenhouse gas emission from coal-fired power plant, there is the need to increase the biomass co-firing ratio. However, high-level replacement of coal with biomass can negatively impact the boiler performances, particularly with regards to ash deposition and tube corrosion.

In our previous study, we investigated the effects of high-ratio co-firing of woody biomass with coal on ash transformation and deposition (slagging) in a small-scale drop tube furnace [9]. We found that the use of a woody biomass with a low ash content (<1 wt%) did not increase the ash deposition (slagging) tendency compared to coal firing even for high biomass ratio of 50% (energy basis). In contrast, a woody biomass with high ash and calcium contents significantly increased slagging tendency during co-firing. However, the effect of the co-firing on tube corrosion was outstanding. The deposits formed on boiler tubes during combustion have a layered structure, with the initial layer (adjacent to tube surface) majorly determining the corrosion behavior [10]. An investigation of the properties of the initial layer of the deposits (i.e., initial deposits) is thus important to precisely elucidating the effects of co-firing on tube corrosion.

A number of previous plant-based studies [11–13] on corrosion during biomass co-firing involved the insertion of a corrosion probe into the boiler, and laboratory corrosion studies [14–18] using synthetic ash have also been conducted over the past few years. Series of corrosion mechanisms involved in: the release of inorganic elements from fuels; the formation of deposits and corrosive gases; and their roles in the various corrosion processes have been explored. Combination of oxidation and sulphidation was reported as the main corrosion mechanism during co-firing biomass, particularly at low ratio, with coal [11–13,15].

This paper reports the results of investigation into the effect of co-firing high ratio of biomass with coal on the formation of the initial deposits collected in real PC boiler, and their effect on the corrosion of boiler tubes. We conducted a demonstration test of the co-firing 25% (energy basis) woody biomass with coal in a commercial 150-MW class pulverized-coal boiler in November 2015, in Japan. The initial deposits from within the furnace wall near the burner and the superheater were collected during the test. The properties of collected initial deposits were investigated in detail. Based on the findings, we developed synthetic deposits, which were used to conduct laboratory-scale corrosion tests of several boiler tube materials under the condition of the furnace wall and superheater environments. The results of the corrosion tests are also discussed in this paper. These results are expected to provide important information and insights to enable the mitigation of ash-

related problems for full-scale implementation of co-firing woody biomass in coal-fired power plants.

## 2. Experimental procedure

### 2.1. Co-firing test

The co-firing test was conducted in a 150-MW class pulverized-coal boiler belong to Nippon Steel & Sumitomo Metal Corporation in Iwate prefecture, Japan. This test, which was conducted in November 2015, was the largest scale of co-firing of high ratio biomass with coal that had been conducted in a coal-fired power plant in Japan. The boiler is equipped with 16 burners, with 8 burners located at two levels. The biomass was separately pulverized in a modified coal mill and supplied to the boiler through four of the upper-level biomass burners as shown in Fig. 1. The main data of co-firing test are presented in Table 1. From this table, the co-firing process was confirmed to proceed stably without reduction of the boiler efficiency. We also confirmed that the emission of NO<sub>x</sub> and SO<sub>x</sub> gases at the boiler exit also reduced to a degree proportional to the co-firing ratio.

### 2.2. Fuel and sampling point

Local Japanese wooden pellets and bituminous coal were used. Their properties are given in Table 2.

The deposits were collected during co-firing and coal firing respectively, for comparison. Water-air-cooled probes installed at different sampling points, as shown in Fig. 1, were used to collect the deposits. To simulate the condition of the heat-transfer tubes in the boiler, the surface temperature of the probes were controlled to 500 and 650 °C for furnace wall and superheater sampling, respectively. After exposure of the probe for 30–150 min, the deposits were carefully collected and weighed. The collected deposits, which weighed approximately 1–3 g, were analyzed to determine their properties, based on which synthetic deposits were then developed.

### 2.3. Analysis method for deposits

The ash samples were analyzed by inductively coupled plasma atomic emission spectroscopy (for SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, CaO, MgO, Fe<sub>2</sub>O<sub>3</sub>, BaO, TiO<sub>2</sub>, and P<sub>2</sub>O<sub>5</sub>), atomic absorption spectrophotometry (for K<sub>2</sub>O, Na<sub>2</sub>O) and infrared spectrophotometry (for SO<sub>3</sub>) to determine their chemical compositions. The water-soluble compounds in the ash were also analyzed according to JISZ-J302-6. Computer-controlled scanning electron microscopy (CCSEM) was used to determine the morphology and mineralogy of all ash deposits. The details about CCSEM procedure are available in another paper [8]. Thermogravimetric analysis (TGA) was used to determine the ratio of the unburned carbon in the deposits.

### 2.4. Corrosion test setup

The tube materials considered in the corrosion tests and their properties are shown in Table 3. Carbon steel (STBA410) and low-alloy steel (STBA22) were used for the furnace wall tubes, while two types of austenitic stainless steels (Ka-SUS304J1HTB and Ka-SUS310J1TB) were used for the superheater tubes. The materials were sourced as long tubes which were then cut and machined into tube segments measuring 20 mm wide, 12 mm long, and with wall thickness of 3 mm. The surfaces of all the specimens were prepared by 600-grit surface finishing and acetone washing.

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