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Co-combustion Behavior of Coal and Carbonized Sludge for Pulverized Coal Combustion Boiler

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Abstract

Co-combustion of municipal sewage sludge in a coal-fired boiler is one of the ways to economically recycle heat. Utilizing biomass fuel as sewage sludge is also a well-known method for reducing emissions of greenhouse gases such as CO_2 and N_2O. The main purpose of this study is to decide the maximum mixing ratio of carbonized sewage sludge for a pulverized coal-fired boiler. The characteristics of the combustibility, the gas emissions and the ash deposition during co-combustion were investigated. The carbonized sewage sludge was produced by heating the sewage sludge at 1073 K under low oxygen ambient. The combustion tests were conducted using a pulverized coal combustion furnace equipped with a refractory wall. The unburned ratio of coal mixed with carbonized sewage sludge relatively decreased since the particle diameter of the carbonized sewage sludge is small and it has a large specific surface area. N_2O, a greenhouse gas, was not produced during co-combustion because the combustion temperature was high enough. It was found that the carbonized sewage sludge additive acts to increase the rate of ash deposition on the tube. The maximum mixing ratio of carbonized sewage sludge for preventing slagging in a pulverized coal-fired boiler is up to 5 wt% was confirmed.

***Keywords*:**
Co-combustion, Carbonized sewage sludge, Ash deposition,

1. Introduction

Co-combustion of municipal sewage sludge in a coal-fired boiler is one of the ways to economically recycle heat. Utilizing biomass fuel as sewage sludge is also a well-known method for reducing emissions of greenhouse gases such as CO_2 and N_2O. Sewage sludge is mushy with a high moisture content, and is an organic compound with a distinctive odor. Therefore, sewage sludge needs to be treated before it can be used as a fuel in a pulverized coal-fired boiler. Producing biomass fuel from sewage sludge by drying, carbonizing and gasifying it is drawing attention in Japan as a way to recycle sludge. The carbonizing of sewage sludge is an effective treatment since it is possible to homogenize the fuel composition and eliminate odors.

A considerable number of studies have been conducted on co-combustion of coal mixed with around 20 wt% of dried sewage sludge. The methods of pulverized coal combustion [1] and fluidized bed coal combustion [2] with dried sewage sludge were studied using a laboratory test furnace. In a temperature range between 973 and 1173 K, which is seen in fluidized bed combustion, the NOx and N_2O concentrations during co-combustion of sewage sludge were higher than during coal combustion [2]. Kupka et al. [3] have evaluated how much ash was deposited during co-combustion, and found that the amount of ash deposition increased as the mixing ratio of dried sewage sludge increased. Moreover, the ash formation after co-combustion [4] and the combustion rate [5] were also investigated. However, dried sewage sludge contains a chlorine component in the amount of a few thousands to tens of thousands of ppm. This high Cl concentration in fuel has been recognized as a serious problem for coal-fired boilers.

The main purpose of this study is to decide the maximum mixing ratio of carbonized sewage sludge for a pulverized coal-fired boiler. First, the carbonized temperature that could decrease the Cl component was evaluated. The carbonized sewage sludge was produced by heating municipal sewage sludge at a temperature of between 773 and 1173 K in a low oxygen atmosphere. Then, combustion tests were conducted using a pulverized coal combustion furnace equipped with a refractory wall. The characteristics of the combustibility, the gas emissions and the ash deposition during co-combustion were investigated. In particular, the ash deposition characteristics are the most important factor to consider when deciding the maximum mixing ratio of carbonized sewage sludge. The ash melting point of sewage sludge is relatively low. As a result, slagging and fouling problems may occur in coal-fired boilers. Deposited ash on the heat exchanger tube reduces the overall heat transfer coefficient due to its low thermal conductivity.

2. Carbonized temperature of sewage sludge

Municipal sewage sludge has a high chlorine content since it is derived from an organic waste material. High temperature carbonization with pyrolysis and gasification reactions could decrease this Cl concentration of sewage sludge. Figure 1 shows the relationship between Cl concentrations and carbonized temperature. Before carbonization, the Cl concentration was over 2000 ppm, and the concentration needs to be reduced to 500 ppm, the same level as coal. The Cl concentration depended on the carbonized temperature as shown in Fig. 1, and the concentration was reduced to 500 ppm at 1073 K because the organic chlorine decomposed. Therefore, we decided a treatment condition as 1073 K under low oxygen atmosphere. Figure 2 shows the photo of sewage sludge after carbonization at 1073 K. The shape is round or elongated, and the diameter is around 10 mm. The carbonized sewage sludge was pulverized less than 75 micrometers for combustion test.

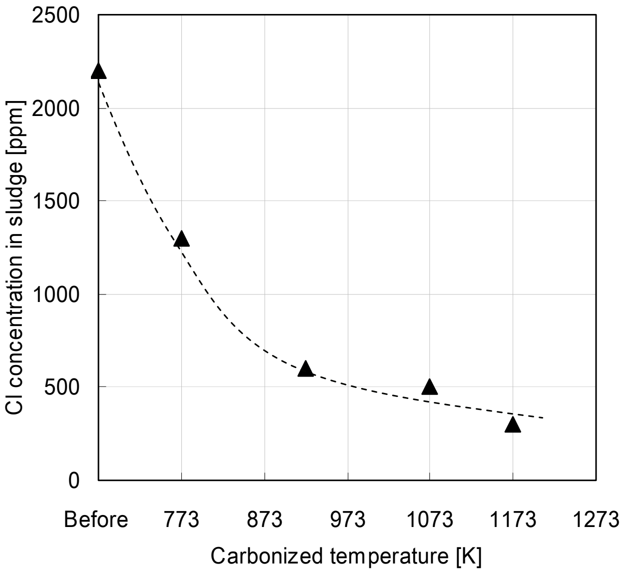


Fig. 1 Carbonized temperature vs. chloride concentration

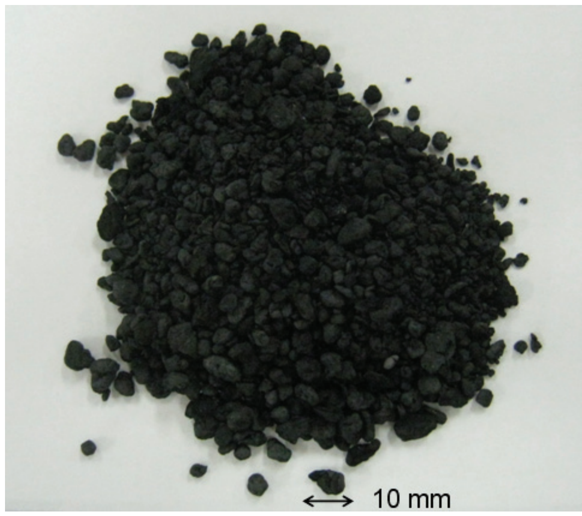


Fig. 2 Photo of sewage sludge after carbonization

3. Experimental

Figure 3 shows a schematic drawing of the pulverized coal furnace employed in this study. The furnace had a length of 3650 mm and an inner diameter of 400 mm. It was insulated with a refractory material to reduce the heat loss. The pulverized coal metrized by the volumetric feeder was transported to the burner with nitrogen gas, and burnt in the furnace with the primary air at ambient temperature and the preheated secondary air at 573 K. When the temperature inside the furnace reached 1473 K by city gas combustion, it switched to pulverized coal combustion. The 15 points in the vertical direction of gas temperature in the furnace was measured with an R-type thermocouple. Concentrations of gases such as CO_2, CO, O_2 and NOx in the furnace and outlet of furnace were analyzed. Fly ash was collected at the cyclone separator located at the furnace outlet, and the unburned carbon in the ash was analyzed using the fly ash. The heat load was fixed at a given value of 60 kW for the different coals tested. The oxygen concentration of the flue gas at the furnace outlet was fixed at a given value of 4% on a dry basis. The ash deposition probe was inserted 1900 mm from the burner at around 1573 K. The temperature and gas compositions at the inserted position were similar to those found in the slagging area in a coal-fired boiler. In our ash deposition test, city gas as auxiliary fuel was supplied to the coal combustion in order to raise the coal particle temperature up to 2000 K. The oxygen concentration of the flue gas at the furnace outlet was also adjusted to about 1% on a dry basis.

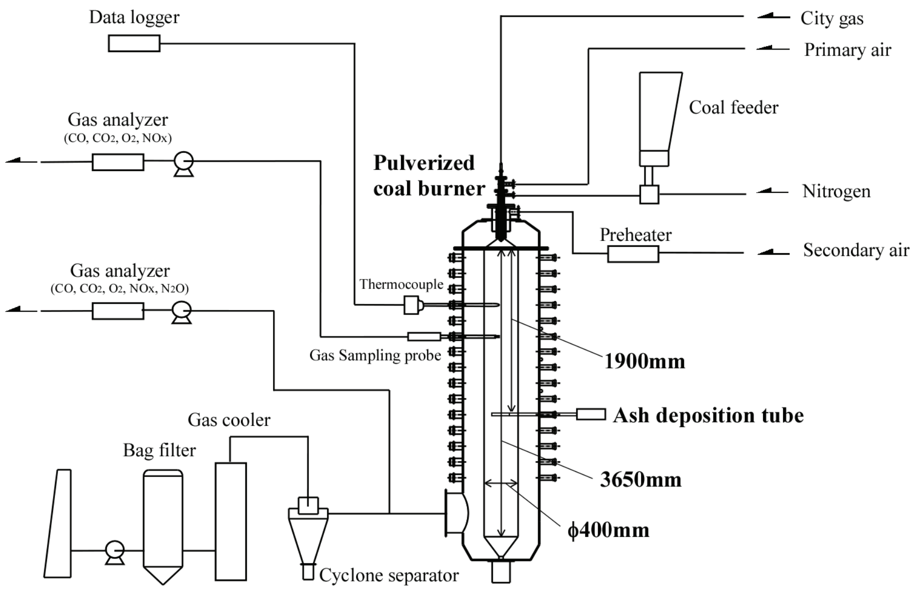


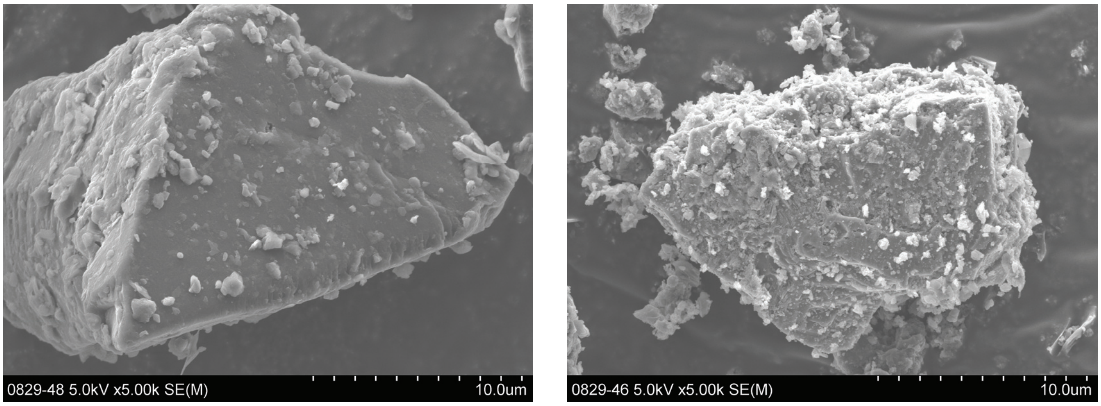
Fig. 3 Schematic drawing of combustion furnace

Table 1 shows the fuel properties. Three types of bituminous coal and sewage sludge to be carbonized at 1073 K were used for the co-combustion test. The fuel ratio in the table denotes the content ratio of fixed carbon to volatile matter in the coal. The fuel ratio and nitrogen content of the carbonized sewage sludge was highest in the fuels, and the sulfur content, ash melting point and heating value were the lowest. The ash concentration in the fuel and specific surface area were highest because the sewage sludge was carbonized under high temperature conditions. Since moisture and volatiles matter was released on carbonization reaction, the surface of the carbonized sewage sludge was textured shown in

Fig. 4. Figure 5 shows the particle diameter distributions of fuels. These fuels were pulverized so that their particles had a diameter of less than 75 micrometers with a 75 % mass fraction. The particle diameter of the carbonized sewage sludge was smallest since fuel with a low Hardgrove Grindability Index (HGI) could be easily pulverized.

Table 1 Fuel properties

	Coal A	Coal B	Coal C	Carbonized sludge
Fuel ratio [-]	1.51	1.18	1.95	4.57
N [wt%-dry]	1.68	1.69	1.68	3.82
S [wt%-dry]	0.58	0.53	0.46	0.23
Cl [wt%-dry]	< 0.05	< 0.05	< 0.05	< 0.05
Ash [wt%-dry]	12.9	5.2	9.0	50.4
Melting point of ash [K] *Oxidized atmosphere	1823	1724	1803	1648
HHV [MJ/kg]	29.6	30.8	31.9	14.5
HGI [-]	54.0	44.8	60.3	80.2
Specific surface area [m^2/g]	7.77	18.00	4.98	105.07



Coal C

Carbonized Sewage Sludge

Fig. 4 SEM photographs of Coal C and Carbonized sewage sludge

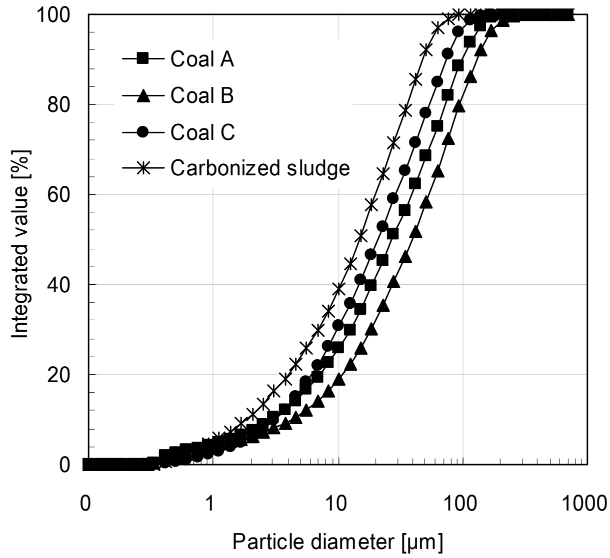


Fig. 5 Particle diameter of coal and carbonized sludge

4. Results and Discussion

4.1 Unburned ratio

The characteristics of co-combusting coal mixed 5 to 20 wt% with carbonized sewage sludge were investigated in this study. The combustibility during co-combustion was evaluated by the unburned ratio U_c^* which means the ratio of unburned carbon to combustible material in fuel as shown in Eq. (1), where *Ash* is the ratio of ash to fuel on a dry basis, and U_c is the ratio of unburned carbon in the ash.

$$U_c^* = \frac{Ash}{1-Ash} \cdot \frac{U_c}{1-U_c} \qquad (1)$$

Figure 6 shows the distribution of the unburned ratio during co-combustion with Coal A and the carbonized sewage sludge. The unburned ratio depends on the fuel ratio, and the combustibility increases and leads to a low fuel ratio. However, the unburned ratio decreased as the mixing ratio of the carbonized sewage sludge with a high fuel ratio increased. It is suggested the decrease in the unburned ratio in the co-combustion resulted from various factors, such as the larger specific surface area and smaller particle diameter. Figure 7 shows the relationship between the unburned ratio and specific surface area, and the results are for three kinds of bituminous coals mixed 5 to 20 wt% with carbonized sewage sludge. The value of the specific surface area under the mixing conditions was used as the weighted average. It was confirmed that the unburned ratio depends on the specific surface area. Since the surface that burned on the fuel's char, which has a larger specific surface, become active, the unburned ratio decreased with co-combustion of the carbonized sludge. Therefore, the combustibility was improved by mixing coal with carbonized sewage sludge.

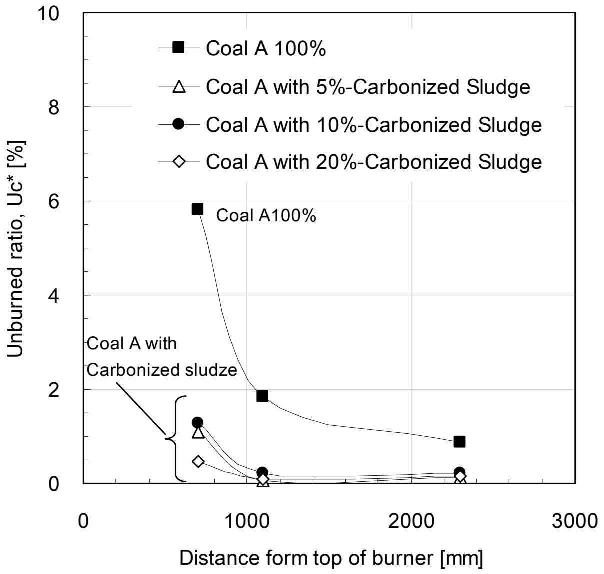


Fig. 6 Distribution of the unburned ratio during co-combustion

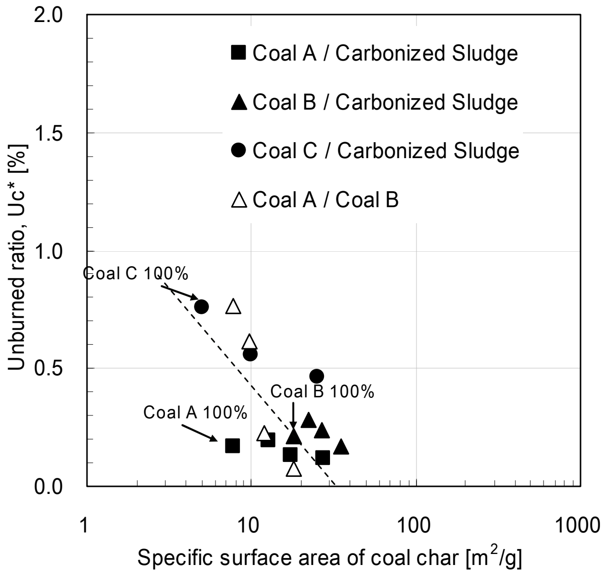


Fig. 7 Unburned ratio vs. specific surface area

4.2 NOx and N_2O emissions

The nitrogen content of carbonized sewage sludge is much higher than in bituminous coal as show in Table 1. Therefore, a higher NOx emission problem may occur with co-combustion compared with coal combustion. Figure 8 shows the relationship between the NOx concentration and fuel ratio. The fuel ratio under mixing conditions was used as the weighted average. The NOx concentrations under mixing conditions of the carbonized sewage sludge have the same tendency as coal combustion. For a fuel ratio up to 1.5, the NOx concentration increased and came to depend on fuel ratio. With a fuel ratio of over 1.5, the NOx concentration decreased. It was considered that the NOx was reduced by the unburned char in the combustion furnace.

In a temperature range between 973 and 1173 K, which is seen in fluidized bed combustion, the NOx and N_2O concentrations during co-combustion of sewage sludge were higher than during coal combustion [2]. N_2O is a well-known greenhouse gas, and it contributes to global warming much more than CO_2 emissions. Figure 9 shows the N_2O concentration under mixing conditions of carbonized sewage sludge. The maximum temperature in the combustion furnace was achieved around 1473 K. N_2O was not produced during co-combustion because the combustion temperature was high enough.

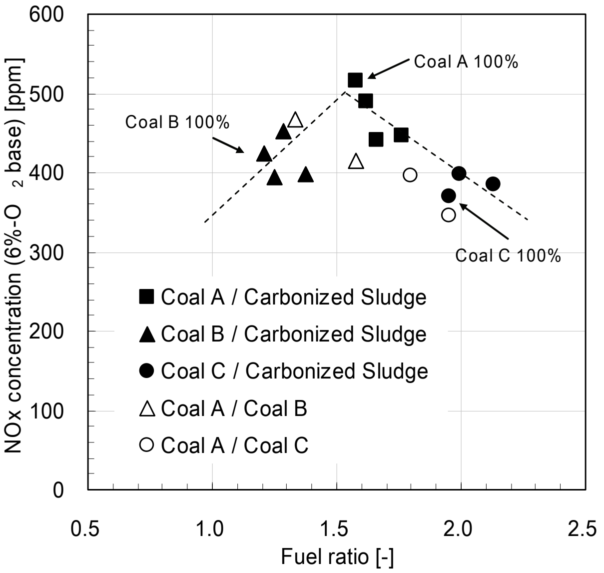


Fig. 8 NOx concentration vs. fuel ratio

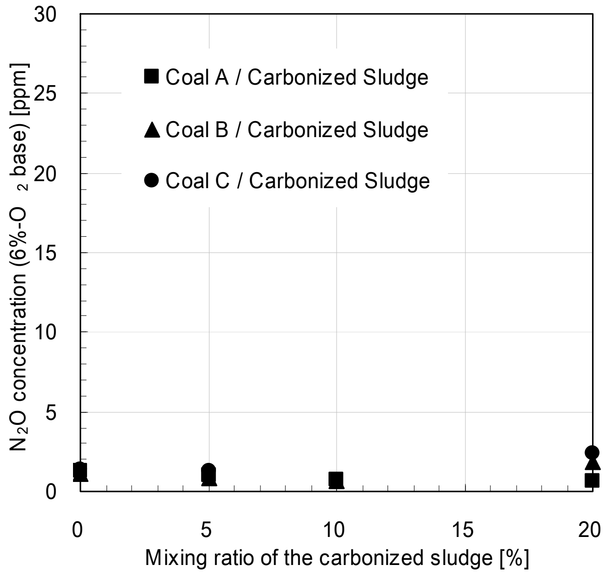


Fig. 9 N_2O concentration under mixing conditions of carbonized sewage sludge

4.3 Ash deposition characteristics

Our research group has investigated the deposition behavior of ash with a low melting point such as brown coal. We conducted an ash deposition test using a refractory furnace and estimated the molten slag fraction in ash using a chemical equilibrium calculation [6]. It was confirmed that the deposition fraction in ash is greatly increased when the molten slag fraction in ash becomes over around 60%. Therefore, the ash deposition characteristics during co-combustion of carbonized sewage sludge can be predicted by our evaluation method.

Table 2 shows the ash composition of three different types of coal and carbonized sewage sludge. Coal A is a bituminous coal with high melting point ash. Coal B is a bituminous coal and Coal D is a sub-bituminous coal, and both coals have ash with a low melting point. The melting point of the ash in carbonized sewage sludge is also low, and the ash has a low SiO_2 content, a high Al_2O_3 content, and a high CaO content. In particular, the P_2O_5 content that is present because of organic and inorganic waste is much higher than that of coals.

First, the molten state of ash was calculated by a chemical equilibrium calculation using FactSage ver. 6.0 software. At high temperatures, ash becomes between liquid and solid phases. The molten slag faction means the ratio of the liquid phase in ash, and it is defined by Eq. (2) below. Input data for the chemical equilibrium calculation consist of temperature, gas concentration around ash and ash composition under the mixing conditions of fuels. For further details, see our published paper [6].

Molten slag fraction in ash [%]
= (Liquid phase) / (Liquid phase + Solid phase) x 100 (2)

Table 2 Ash composition

		Coal A	Coal B	Coal D	Carbonized sludge
Ash [wt%-dry]		12.9	5.2	2.7	50.4
SiO_2	[wt%-ash]	67.0	59.1	52.0	16.9
Al_2O_3	[wt%-ash]	22.7	25.3	20.3	31.2
CaO	[wt%-ash]	1.5	1.2	6.0	10.5
TiO_2	[wt%-ash]	1.0	0.5	1.1	0.7
Fe_2O_3	[wt%-ash]	4.6	8.9	12.1	7.2
MgO	[wt%-ash]	0.5	1.5	1.9	2.3
Na_2O	[wt%-ash]	0.7	0.6	0.4	0.5
K_2O	[wt%-ash]	1.0	2.4	0.7	1.6
P_2O_5	[wt%-ash]	0.4	0.4	0.1	26.2
MnO	[wt%-ash]	0.0	0.0	0.1	0.3
SO_3	[wt%-ash]	0.6	0.1	5.2	0.3
BaO	[wt%-ash]	—	—	—	1.0
ZnO	[wt%-ash]	—	—	—	0.3
CuO	[wt%-ash]	—	—	—	0.2
SrO	[wt%-ash]	—	—	—	0.1

Figure 10 shows the results of calculating the molten slag fraction in ash at a temperature of 1573 K under mixing conditions. The molten slag fraction in ash under coal combustion conditions, Coal A and B or Coal A and D, show no local maximal values. However, the molten slag fraction during co-combustion of carbonized sewage sludge show a curve with local maximal values, and the highest value occurs when the mixing ratio of the carbonized sewage sludge is around 20 wt%. Since ash deposition rate was predicted to increase when the molten slag fraction in ash reaches more than 60%, the allowable mixing ratio of the carbonized sewage sludge was recommended to be less than 15 wt% for co-combustion.

The ash deposition test was evaluated by examining the deposition fraction of ash, and it is defined in the following Eq. (3). Ash deposition probe to be water-cooled, made of stainless steel, was inserted 1900 mm from the burner where the temperature was around 1573 K. In this test, city gas as an auxiliary fuel was supplied to the furnace in order to raise the particle temperature up to 2000 K. The oxygen concentration of the flue gas at the furnace outlet was also adjusted to about 1% on a dry basis.

Deposition fraction of ash [%]

= (Deposition mass of ash on tested probe) / (Fed mass of ash on the probe) x100 (3)

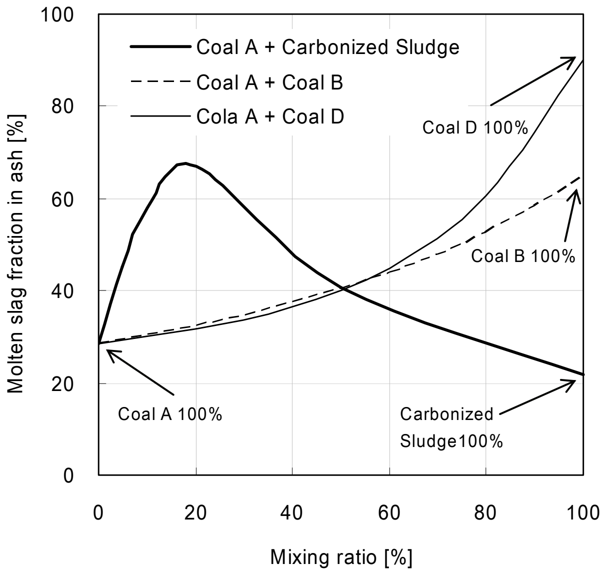


Fig. 10 Calculated molten slag fraction in ash under mixing conditions

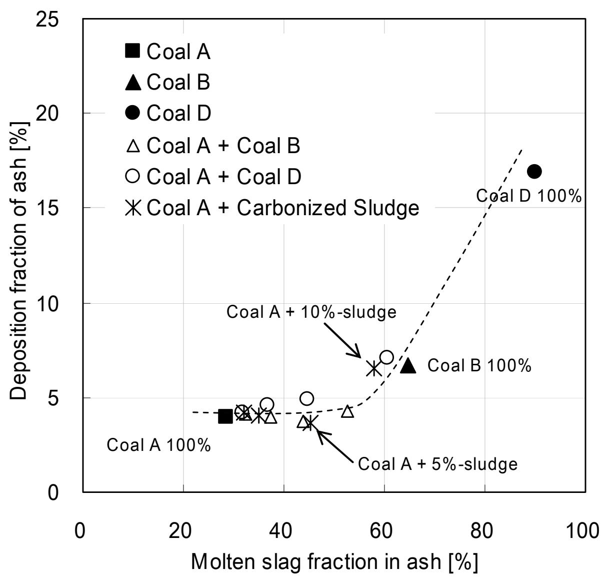


Fig. 11 Relationship between deposition faction of ash and molten slag fraction in ash

Figure 11 shows the experimental results of the deposition fraction of ash. The mixing ratio of the carbonized sewage sludge was 1, 2, 5 and 10 wt%. For reference, the results of coal combustion are also shown in Fig. 11. The deposition fraction of ash was greatly increased when the molten slag fraction in ash become over around 60%. Therefore, around 60% of molten slag fraction is the critical point for increasing ash deposition. Up to 5 wt% of the carbonized sewage sludge in mixed fuel, the deposition fraction of ash was the same level as that of Coal A combustion. However, mixing rate of the carbonized sewage sludge was 10 wt%, the molten slag fraction in ash reached the critical point. The ash deposition fraction of coal B, which has not been used for coal combustion in our practical coal-fired boiler, was the same level as that of 10 wt% of the carbonized sewage sludge mixture. Therefore, it is confirmed the maximum mixing ratio of carbonized sewage sludge to prevent slagging in a pulverized coal-fired boiler is up to 5 wt%.

Conclusion

The carbonization of sewage sludge and co-combustion test with coal and the carbonized sewage sludge were conducted using pulverized coal combustion furnace. The following findings were obtained:

1. The chlorine concentration in sewage sludge can be reduced by high-temperature carbonization, and the concentration is reduced to 500 ppm at 1073 K at a carbonized temperature.
2. The unburned ratio of coal mixed with carbonized sewage sludge relatively decreases since the particle diameter of the carbonized sewage sludge is small and it has a large specific surface area.
3. N_2O, a greenhouse gas, is not produced during co-combustion because the combustion temperature is high enough.
4. It was found that the carbonized sewage sludge additive acts to increase the rate of ash deposition on the tube. It is confirmed the maximum mixing ratio of carbonized sewage sludge for preventing slagging in a pulverized coal-fired boiler is up to 5 wt%.

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