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A Study on the Co-Combustion Characteristics of Coal and Bio-SRF in CFBC

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Abstract: Bio-SRF based on livestock waste has low heating value and high moisture content. The concentration of toxic gases such as SOx, NOx, and HCl in the flue gas is changed according to the composition of fuel, and it has been reported. Therefore, the study of fuel combustion characteristics is necessary. In this study, we investigated combustion characteristics on the blended firing of coal and Bio-SRF (bio-solid refused fuel) made from livestock waste fuel in CFBC (circulating fluidized bed combustor). The raw materials for manufacturing Bio-SRF include agricultural waste, herbaceous plants, waste wood, and vegetable residues. Bio-SRF, which is formed from organic sludge, has a low heating value and a high moisture content. Bio-SRF of livestock waste fuel is blended with different ratios of coal based on heating values when coal is completely combusted in CFBC. In the result of experiment, the combustor efficiency of calculated unburned carbon concentration in the fly ash shows 98.87%, 99.04%, 99.64%, and 99.71% when the multi co-combustion ratio of livestock waste fuel increased from 100/0 (coal/livestock waste) to 70/30 (coal/livestock waste). In addition, the boiler efficiency is shown to be 86.23%, 86.30%, 87.24% and 87.27%. Through the experimental results, we have identified that co-combustion of livestock waste fuel does not affect boiler efficiency. We have systematically investigated and discussed the temperature changes of the internal combustor, compositions of flue gases, solid ash characteristics, and the efficiency of combustion and of the boiler during co-combustion of coal and Bio-SRF.

Keywords: CFBC boiler; co-combustion; Bio-SRF; livestock waste fuel; heat and mass balance

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1. Background

The depletion of fossil energy sources and the growing concern for global warming have accelerated developments in renewable energy technologies such as solar power, wind power, geothermal energy, and bioenergy. The definition of "new and renewable energy" varies by country, but in Korea, it is defined as solar, wind, hydropower, marine, geothermal, bio, and waste energy under the Act on the Development, Use, and Distribution of New and Renewable Energy [1]. Solar, wind, and geothermal energy are sustainable, do not emit greenhouse gases, and are considered clean future energy sources; however, they have the disadvantage of low economic feasibility because of the difficulties associated with supplying large amounts of energy due to low energy density and high-cost facility investment. The development and utilization of biomass and waste energy, which are highly economical and can use existing coal power generation facilities, have emerged as a feasible solution to this problem.

Waste co-combustion has increased the energy supply from 2% in 2012 to meet the required energy supply of 10% by 2024 under the management and operation guidelines of the new and renewable energy supply mandate and the fuel blending mandate (Notification No. 2015-155 of the Ministry of Trade, Industry, and Energy), which require the energy supply using new and renewable energy to exceed a certain percentage of

the total generation to suppliers with power generation facilities (>500 MW) that rely on conventional energy sources. Regulations on the production of waste-derived fuels and post-combustion emissions are well prepared [2]. CFBC to using the waste-derived fuels is more suitable than other technologies [3–7] for the production of solid waste fuels and utilization of heat.

Biomass contains waste with an organic content of 40% or higher that is derived from animals and plants, such as livestock manure, sewage sludge, and food waste. With the recent strengthening of regulations to prevent environmental pollution, various solutions are being developed for the reduction of organic waste emissions and the conversion of waste into energy [8]. Waste energy can be used as a solid fuel product after recovery and processing. In Korea, through the Resource Recycling Act of 2013, existing solid fuel products such as RDF (refuse derived fuel), RPF (refuse plastic fuel), and SRF (solid refused fuel) are integrated and managed by classifying them into SRF and Bio-SRF. Waste used as raw materials for manufacturing SRF includes household waste (excluding food products), waste synthetic oil, and waste tires. The raw materials for manufacturing Bio-SRF includes agricultural waste, herbaceous plants, waste wood, and vegetable residues. The emission concentrations of acidic gases such as Sox, NOx, and HCl, which are harmful gases present in the combustion exhaust, increase according to the fuel characteristics. Moreover, Bio-SRF, which is formed from organic sludge, has a low heating value and high moisture content [9]. Therefore, investigating the combustion characteristics of each fuel is crucial [10–13].

Co-combustion of biomass and waste has progressed over the decades with pilot and full-scale systems research [14–16]. Co-combustion system operations are typically CO_2 and other greenhouse gas emissions and thermal efficiency changes in co-fired power plants and utility boilers have been studied. However, problems related to boiler slagging, contamination, and corrosion still remain, so laboratory experiments such as drop tube furnace, thermogravimetric analysis, and other laboratory equipment have recently been conducted; these new biomass and waste types are being studied and evaluated, and it is necessary to explore optimal co-combustion conditions and to explore material synergies [17].

Research on co-combustion has been conducted on biomass and waste, but recently, research has been conducted on selective fuels. In addition to biomass and SRF, Bio-SRF, oil shales, and fuels including caking coal are widely studied [18,19].

In this study, Bio-SRF and coal, which are raw materials obtained from livestock waste fuel, were blended and burned using CFBC technology to examine their combustion characteristics. Bio-SRF was blended with livestock waste fuel in proportions of 10%, 20%, and 30% for CFBC based on the amount of heat from coal combustion. The temperature change in the combustor during co-combustion was determined, and the combustion and boiler efficiencies were calculated by analyzing the exhaust gas, bottom ash, and fly ash.

2. Experimental Materials and Methods

2.1. Experimental Apparatus

The circulating fluidized bed boiler used in the experiment has a capacity of 0.1 MWth and is primarily composed of three parts—a combustion unit, circulation unit, and convection heat transfer unit (back pass), as shown in Figure 1. The internal diameter of the combustor is 0.2 m, and its height is 10 m. A water wall evaporator is installed 3 and 6 m above the dispersion plate. A total of four hoppers are provided to inject materials (fuel, sand, and limestone) required for boiler operation. A screw conveyer was used for the controlled injection of fuel and injected materials. The fuel and materials were injected to the lower part of the combustor over the sand bed. The start-up and operation procedures were the same as in other CFBC boilers [20]. A cyclone dust collecting unit and a loop seal were installed to collect the scattered circulating material and circulate the collected material in the combustor, and a convection pass was configured with an economizer and air preheater. Primary air for the combustion of fuel and fluidization in the circulating fluidized bed boiler was supplied after primary heating in the convection heat exchanger

using a forced draft fan, and a secondary air fan was used to prevent combustion of Bio-SRF during heating and fuel injection.

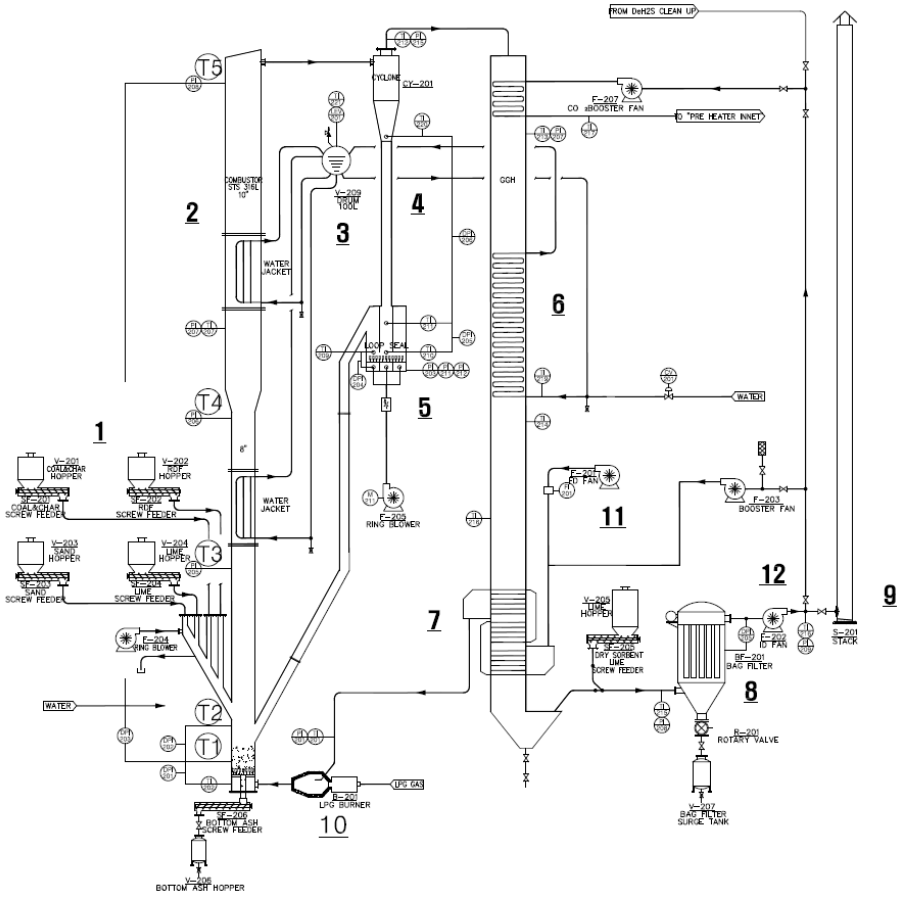


Figure 1. Schematic diagram of 0.1 MWth CFBC boiler. (1) Fuel and material injection unit, (2) combustor, (3) steam and water drum, (4) cyclone, (5) loop-seal, (6) economizer, (7) air preheater, (8) bag filter, (9) stack, (10) start up burner, (11) primary air fan, (12) induced draft fan.

The gas side flow circuit is shown below:

Air from primary air fan → Air preheater inside → Combustor → Cyclone → Convection pass (economizer and air preheater outside) → Bag filter → Induced draft fan → Stack.

The water and steam circuit are shown below:

Water from BFWP (boiler feed water pump) → Economizer → Steam drum → Downcomer → Water wall evaporator → Drum → Final steam exit.

For the experiment, boiler feed water was supplied to the drum installed at the top of the CFBC boiler plant and water was supplied to the water wall evaporator installed in the combustor. In order to generate the combustion of the fuel injected in the combustor, the fluidized sand was heated by a start-up burner using LPG gas as fuel up to 500 °C. After confirming that the injected sand circulated and the DP (differential pressure) of the loop-seal increased, the temperature was increased to over 800 °C by injecting fuel into the combustor.

Four hoppers were used for material injection, and cool, livestock waste and sand were stored separately; the injection amount was adjusted according to the blending ratio. The installed thermocouple was K-type and the use temperature is −270–1260 °C. The thermocouple installed in the CFBC combustor prevents abrasion and corrosion due to fluid material (sand) through the thermowell.

2.2. Fuel Analysis

Industrial and elemental analyses were performed to identify the components of coal and livestock waste fuel used in the co-combustion experiments. Indonesian bituminous coal was used as one of the fuels in the experiment. Livestock waste fuel, which is an auxiliary fuel, was provided and wood chips were blended with dehydrated manure cakes and dried. Table 1 presents the results of the industrial and elemental analyses of the fuel used in the experiment. The moisture content of the bituminous coal and the livestock waste fuel was 22.8 wt.% and 14.46 wt.% because the fuel was stored outdoors, resulting in water re-adsorption due to dew and rain. As the bituminous coal used in the experiment contained 28.38 wt.% of volatile matter and 39.68 wt.% of fixed carbon, the combustion rate was expected to be slow; however, the solid-fueled livestock waste fuel contained 10.26 wt.% of fixed carbon and 50.24 wt.% of volatile matter, confirming the presence of a large amount of volatile matter compared with fixed carbon. The elemental analysis indicated that the content of nitrogen (N) and sulfur (S) in the livestock waste fuel was 2.33 wt.% and 1.23 wt.%, which were approximately twice as high as those in bituminous coal (1.03 wt.% and 0.53 wt.%). In addition, it was confirmed that the livestock waste fuel converted into solid fuel had a high ash content of 25.04 wt.%, and the high heating value (HHV) of coal and livestock waste fuel was 5091 kcal/kg (21.3 MJ/kg) and 3440 kcal/kg (14.4 MJ/kg), respectively.

Table 1. Properties of coal and livestock waste fuel.

Item		Weight Fraction (%)	
		Coal	Livestock Waste Fuel
Proximate analysis	Moisture	22.8	14.46
	Volatile matter	28.38	50.24
	Fixed carbon	39.68	10.26
	Ash	9.14	25.04
Ultimate analysis	Carbon	67.90	37.23
	Hydrogen	4.88	4.92
	Nitrogen	1.03	2.33
	Oxygen	16.52	29.25
	Sulfur	0.53	1.23
High Heating Value			
as received [kcal/kg]		5091	3440
as received [MJ/kg]		21.3	14.4

2.3. Combustion Test Conditions and Composition of Blended Fuel

To determine the blending ratio of coal and organic sludge, a combustion experiment was conducted using only bituminous coal, and the combustor was maintained at a stable state. During elemental analysis of coal and livestock waste fuel, moisture was removed during the pre-treatment process of the fuel before analysis, which altered the composition of the fuel compared with the actual fuel. As shown in Table 2, the characteristics of the blended fuel obtained by correcting for the moisture content of the fuel were recalculated. Livestock waste fuel was blended and burned at co-combustion ratios of 10%, 20%, and 30% of the heat input amount of 97,340 kcal/h based on the heat input amount of coal in the combustion experiment using only bituminous coal. The corresponding co-combustion ratios of the livestock waste fuel used in the experiment were 10.40%, 19.71%, and 29.26%. As the co-combustion ratio of the livestock waste fuel determined using industrial analysis of bituminous coal and blended fuel increased from 100/0 to 70/30, the volatile content of the fuel increased by approximately 9% from 28.38 wt.% to 36.68 wt.%; therefore, it was expected that there would be excess calories in the upper part because of the increase

in the combustion gas temperature. In addition, the fixed carbon content decreased by nearly 10% from 39.68 wt.% to 28.51 wt.%, and ash increased by approximately 15% from 9.14 wt.% to 15.18 wt.%. Therefore, the temperature of the boiler sand layer decreased. After reanalyzing the elemental composition by correcting for the moisture content in the fuel, the carbon content in the fuel decreased by 5% from 52.38 wt.% to 49.68 wt.%, 47.38 wt.%, and 45.15 wt.%, as the co-combustion rate of the livestock waste fuel increased from 100/0 (coal/livestock waste) to 70/30 (coal/livestock waste). By contrast, the nitrogen content in the fuel increased from 0.80 wt.% to 1.22 wt.%, and the oxygen content increased from 10.60 wt.% to 13.88 wt.%; however, there was no significant change in the content. The content of sulfur in the blended fuel increased from 0.53 wt.% to 0.8 wt.% and that of HCl from 0.02 wt.% to 0.25 wt.% as the co-combustion ratio of the livestock waste fuel increased from 100/0 (coal/livestock waste) to 70/30 (coal/livestock waste). In addition, the industrial analysis results (Figure 2) indicated that as the co-combustion rate of the livestock waste fuel increased from 100/0 (coal/livestock waste) to 70/30 (coal/livestock waste), the fixed carbon content decreased from 39.68 wt.% to 28.51 wt.%, the volatile content increased from 28.38 wt.% to 36.68 wt.%, and the ash content increased from 9.14 wt.% to 15.18 wt.%. The calculation of the HHV of the fuel based on the blending ratio revealed that as the co-combustion rate of livestock waste fuel increased from 100/0 (coal/livestock waste) to 70/30 (coal/livestock waste), the heating value of the blended fuel decreased to 5085 kcal/kg (21.3 MJ/kg), 4839 kcal/kg (20.3 MJ/kg), 4628 kcal/kg (19.4 MJ/kg), and 4421 kcal/kg (18.5 MJ/kg). Although the co-combustion ratio of the livestock waste fuel was calculated based on the heat input during the combustion experiment using only coal, it was affected by the errors in the fuel input amount of the screw conveyer, as the amount of the livestock waste fuel increased.

Table 2. Characteristics of blended fuel.

	Coal/Livestock Waste Fuel (100/0)	**Coal/Livestock Waste Fuel (90/10)**	**Coal/Livestock Waste Fuel (80/20)**	**Coal/Livestock Waste Fuel (70/30)**
Inlet heating value [kcal/h]	97,340	90,287	95,300	96,291
Fuel characteristics [wt.%]				
CO_2	0.14	0.17	0.20	0.22
C	52.38	49.68	47.38	45.15
H	3.77	3.83	3.88	3.93
N	0.80	0.96	1.09	1.22
S	0.37	0.45	0.52	0.58
O	10.60	11.78	12.83	13.88
HCl	0.01	0.08	0.14	0.20
H_2O	22.80	21.58	20.58	19.63
Inert	8.85	11.10	12.95	14.69
HHV				
as calculation [kcal/kg]	5085	4839	4628	4421
as calculation [MJ/kg]	21.3	20.3	19.4	18.5

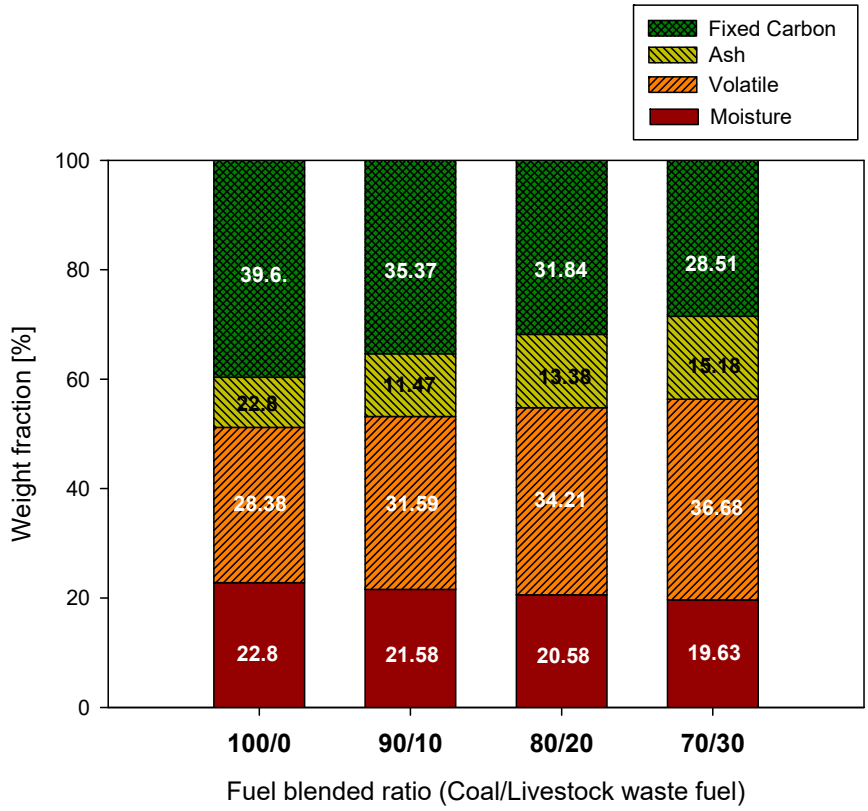


Figure 2. Proximate analysis of blended fuel.

3. Results and Discussion

3.1. Combustor Internal Temperature

Figure 3 presents the results of the co-combustion experiment using only bituminous coal and livestock waste fuel in the circulating fluidized bed boiler. The temperature measurement of the boiler (T1 to T5) was installed according to the height of the combustor as shown in Figure 1. The air nozzle was installed at 0.45 m for air dispersion, and the sand layer in the combustor (combustor beds one and two) was maintained at 900 °C. The temperature of the free board one, which was 4.35 m above the air nozzle, was reduced to 770 °C because of the secondary air inflow. In addition, the temperature of free board two, which was 5.50 m above the air nozzle, was 800 °C, and the combustor outlet, which was 9.30 m above the air nozzle, operated at 780 °C. Based on these results, the test results obtained by increasing the co-combustion rate of livestock waste fuel to 90/10 (coal/livestock waste), 80/20 (coal/livestock waste), and 70/30 (coal/livestock waste) were compared, as shown in Figure 3. When the blending ratio of livestock waste fuel was increased from 90/10 (coal/livestock waste) to 70/30 (coal/livestock waste), the combustion was similar to that for bituminous coal regardless of the characteristics of the blended fuel because of the increased blending ratio. These results are consistent with those of a previous study by T. Saikaew et al. [21] on the combustion characteristics of biomass containing sawdust, rice husks, and coconut shells in a circulating fluidized bed.

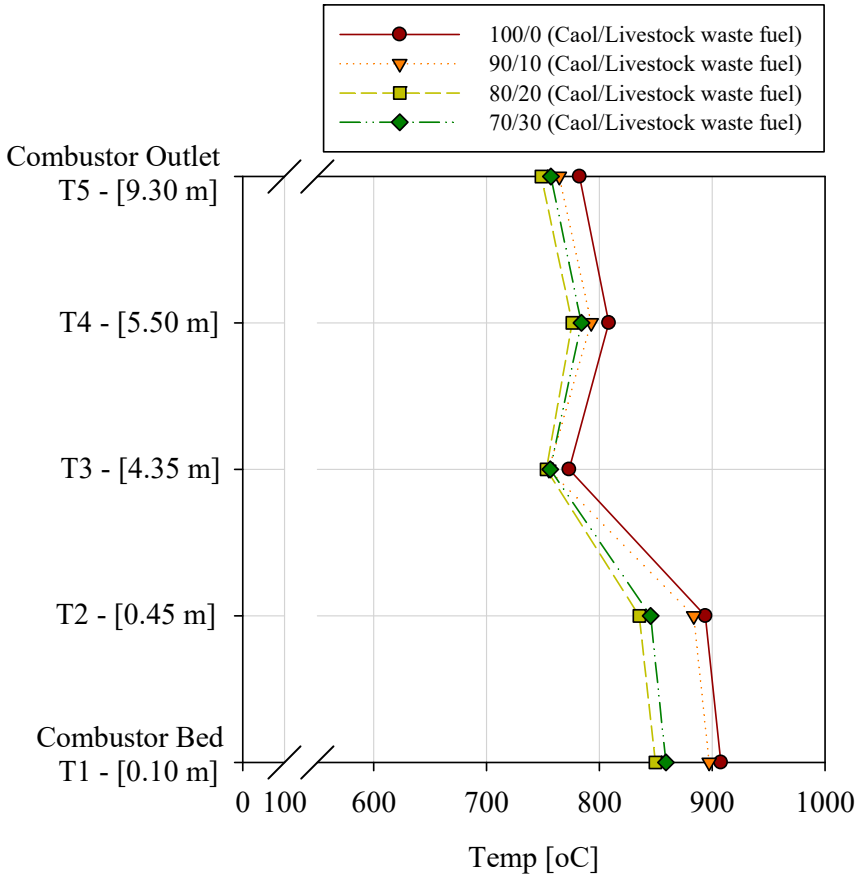


Figure 3. Combustion characteristics of livestock waste fuel at combustor.

As the co-combustion ratio of the livestock waste fuel increased from 100/0 (coal/livestock waste) to 70/30 (coal/livestock waste), the internal temperature of the boiler decreased, as shown in Table 2. As shown in the calculation results of the higher heating value of the blended fuel in Table 2, the heating value of the fuel at the time of burning the bituminous coal was 5085 kcal/kg (21.3 MJ/kg); however, as the blending ratio increased, the heating value of the blended fuel decreased to 4839 kcal/kg (20.3 MJ/kg), 4628 kcal/kg (19.4 MJ/kg), and 4421 kcal/kg (18.5 MJ/kg). The decrease in the heating value of blended fuel was due to the error in the fuel injection amount of the screw conveyer mentioned above. Figure 4 shows the temperatures of the cyclone, loop-seal, and back-pass, which are the combustor rear facilities, during the experiment. The temperature change of the rear equipment of the boiler according to the blending ratio was 100/0 (coal/livestock waste) to 70/30 (coal/livestock waste), and as the blending ratio increased, the temperature of the loop seal and the cyclone outlet decreased from 600 °C to 450 °C; however, the temperatures of the economizer outlet and the bag filter were maintained without significant changes at 140 °C and 75 °C, respectively, under all combustion conditions. The reason for the decreases in the cyclone outlet and the loop-seal temperature were that as the blending ratio increases, the internal temperature of the combustor decreases (Figure 3), the temperature of the circulated ash decreases, and the supply of heat sources to the cyclone and loop-seal decreases. However, the reason there was no change in the temperature difference at the economizer outlet and bag filter is that in the economizer and bag filter, convective heat transfer by combustion gas acts as the main heat source and is less affected by the scattered ash.

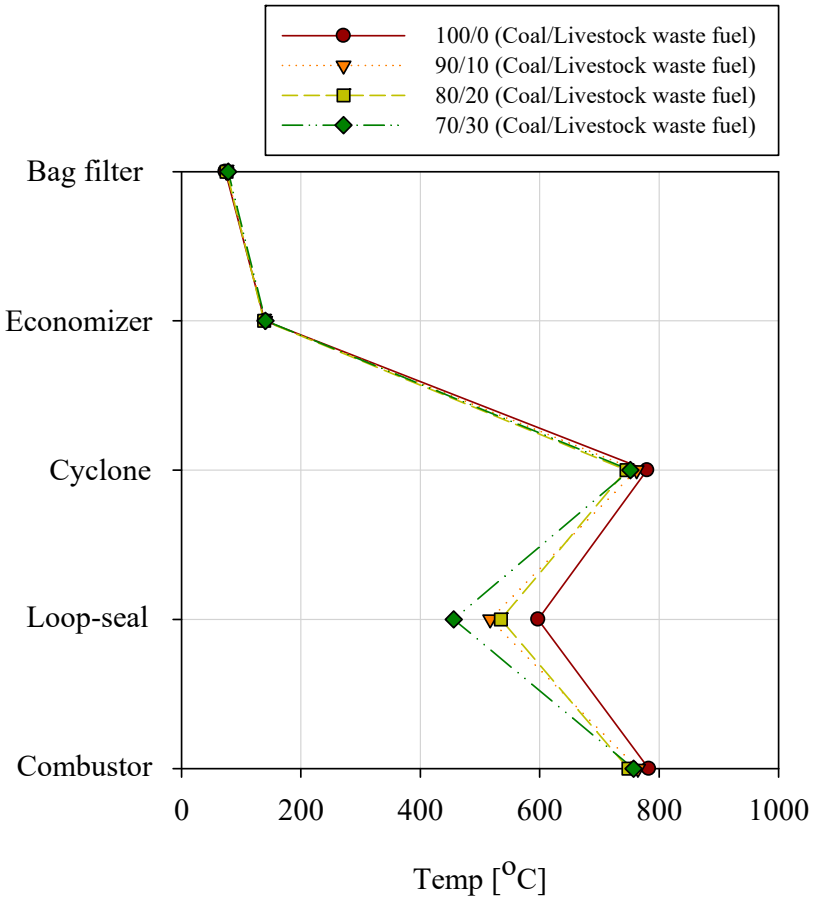


Figure 4. Combustion characteristic of livestock waste fuel at CFBC boiler.

3.2. Combustion Gas Analysis Results

The components of the combustion gas generated during the co-combustion of bituminous coal and livestock waste fuel were analyzed for CO, CO_2, NO, SO_2, and O_2 concentrations using a real-time gas analyzer (ABB, Cary, NC, USA). As shown in Figure 5 (O_2), as the co-combustion ratio of the livestock waste fuel increased from 100/0 (coal/livestock waste) to 70/30 (coal/livestock waste), the concentration of O_2 in the combustion gas increased to approximately 9.90 to 11.14 vol.%. This is because, as in the fuel characteristic analysis shown in Table 2, when the co-combustion ratio of the amount of heat generated by the fuel injected for co-combustion increased from 100/0 (coal/livestock waste) to 70/30 (coal/livestock waste), the amount of heat generated decreased from 5085 kcal/kg (21.3 MJ/kg) to 4421 kcal/kg (18.5 MJ/kg), but the amount of injected air was supplied at a constant flow rate without change, and therefore the excess air ratio increased. As the blending ratio of bituminous coal and livestock waste fuel increased from 100/0 (coal/livestock waste) to 70/30 (coal/livestock waste), the concentration of SO_2 increased from 80 to 200 ppm, as shown in Figure 5 (SO_2). This is because the content of sulfur (S) in the blended fuel increased from 0.37 to 0.58 wt.% as the blended consumption ratio increased, as shown in Table 2. As a result of calculating the conversion rate of sulfur (S) in the fuel (Table 3), it was shown that it increased from 0.285 to 0.421% as the blended consumption ratio increased from 100/0 (coal/livestock waste) to 70/30 (coal/livestock waste). The conversion rate of each component in the combustion gas was mol base, and it was calculated by dividing the number of mol of each component by the content of the total generated gas based on 1 kg of fuel. The generation of NOx in the combustion gas decreased slightly as the blending ratio of the livestock waste fuel increased from 100/00 (coal/livestock waste) to 70/30 (coal/livestock waste). In the fuel analysis results shown in Table 1, the nitrogen (N) content contained in livestock waste fuel was 2.33 wt.%, which

was approximately twice the nitrogen (N) content contained in bituminous coal 1.03 wt.%. However, when the blending ratio of bituminous coal to livestock waste fuel increased from 100/0 (coal/livestock waste) to 70/30 (coal/livestock waste), the nitrogen (N) content of the blended fuel was 0.80 to 1.22 wt.% (Table 2), and the increase was small. This is because the combustor temperature slightly decreased, reducing the generation of high-temperature NOx (Figure 3). These findings indicate that the combustion characteristics of the previous biomass, RDF, and RPF are comparable [3,5]. In addition, as shown in Figure 5 (CO), the concentration of CO in the combustion gas was maintained at 300 ppm or less, confirming that it was completely burned in the combustor regardless of the co-combustion ratio of the livestock waste fuel. As shown in Figure 5, the analysis of HCl in the combustion gas showed that the emission concentration increased slightly in the range of 3.45 to 5.27 ppm. This is because the conversion rate of HCl in the fuel during co-combustion decreased from 0.45 to 0.04 as the co-combustion ratio increased from 100/0 to 70/30; however, the content of HCl in the blended fuel increased significantly from 0.01 wt.% to 0.20 wt.% (Table 2), as shown in Table 3.

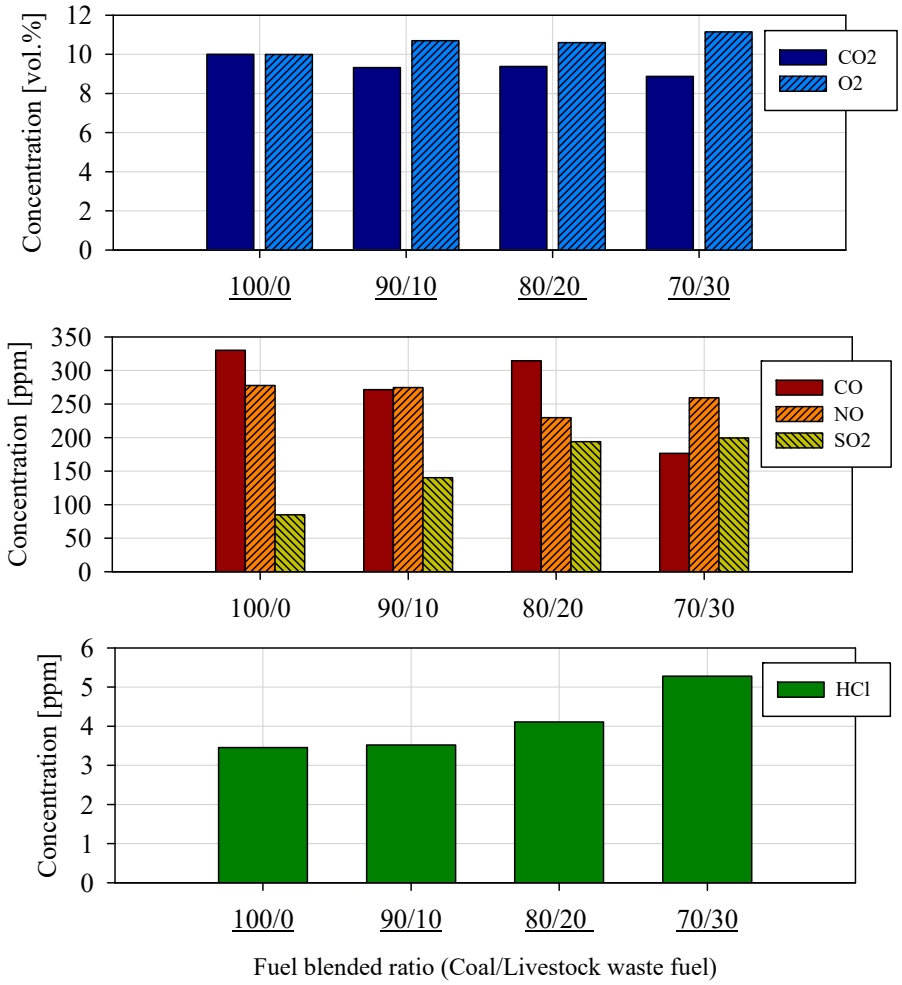


Figure 5. Fuel gas concentration from the co-combustion.

Table 3. Mass balance.

	Coal/Livestock Waste (100/0)	Coal/Livestock Waste (90/10)	Coal/Livestock Waste (80/20)	Coal/Livestock Waste (70/30)
Theoretical air [Nm^3/kg]	5.396	5.131	4.905	4.684
Air/Fuel ratio [-]	1.85	1.97	1.97	2.08
Fuel conversion [-]				
SOx($S \rightarrow SO_2$)	0.285	0.393	0.452	0.421
NOx($N \rightarrow NO$)	0.019	0.158	0.111	0.113
N_2O($N \rightarrow N_2O$)	0.030	0.030	0.030	0.030
HC($C \rightarrow CH_4$)	0.001	0.001	0.001	0.001
HCl	0.450	0.068	0.044	0.040
CO($C \rightarrow CO$)	0.003	0.003	0.003	0.002
CO_2 from fuel	0.986	0.988	0.995	0.996
Flue gas [$kmol/kg_{fuel}$]	0.473	0.477	0.457	0.461
Ash and solid Ca_{fuel} [kmol/kg]	8.1×10^{-6}	1.0×10^{-5}	1.2×10^{-5}	1.3×10^{-5}
Solid discharge [-]	0.102	0.125	0.141	0.161
Unburned C [-]	5.06×10^{-3}	3.88×10^{-3}	1.41×10^{-5}	3.19×10^{-5}
C_{ash} [%]	4.966	3.101	0.010	0.019
Bottom Ash ratio [-]	0.2	0.2	0.2	0.2

3.3. Heat and Mass Balance

As shown in Table 3, mass balance was calculated based on the mol ratio, which was based on the results of the co-combustion experiment of bituminous coal and livestock waste fuel [22]. The A/F (Air/Fuel) ratio calculated based on the combustion gas concentration was 1.85 to 2.08, which was larger than the typical value of 1.2. The A/F ratio of the actual combustion air was 1.2, but this was due to air leakage at the experimental apparatus coupling. Through the industrial analysis results of the fly ash recovered in the bag filter, the conversion rate of the fuel to the ash and the unburned carbon component was confirmed. The conversion ratio of injected fuel to the ash from 0.102% to 0.125%, 0.141%, and 0.161% increased from the fuel analysis results shown in Table 2 to 9.14 wt.%, 11.47 wt.%, 13.38 wt.%, and 15.18 wt.% as the ash content in blended fuel increased from 100/0 (coal/livestock waste) to 70/30 (coal/livestock waste). Calculations based on the industrial analysis results of the fly ash recovered during the co-combustion experiment of livestock waste fuel showed that as the co-combustion rate of livestock waste fuel increased from 100/0 (coal/livestock waste) to 70/30 (coal/livestock waste), the carbon component in ash decreased to 4.96%, 3.10%, 0.01%, and 0.01%. This means that combustion is completed in the combustor with an increase in volatile content and a decrease in fixed carbon in the blended fuel (Table 2).

As shown in Table 4, combustion and boiler efficiencies were calculated based on the gases generated during the bituminous coal burning and livestock waste fuel blending experiment and the results of the solid analysis collected from the bag filters. The combustion efficiency and boiler efficiency were calculated using the input/output reference and the heat loss reference methods, and the results of this experiment were obtained using the heat loss reference method, as shown in Equation (1). The unburned loss (B_L) of Equation (1) defines only the energy lost to CO_2 by oxidation of carbon (C) supplied from

injected fuel without combustion, as shown in Table 4. As the co-combustion rate of the livestock waste fuel increased from 100/0 (coal/livestock waste) to 70/30 (coal/livestock waste), the combustion efficiency slightly increased from 98.87% to 99.71%. Based on the boiler temperature change observed in Figures 3 and 4 and the gas analysis result shown in Figure 5, it was confirmed that as the co-combustion rate of the livestock waste fuel increased, the ratio of fixed carbon in the blended fuel decreased and the volatile content increased, thereby increasing the combustion efficiency of the fuel in the combustor. As shown in Equation (2), the boiler efficiency was calculated by adding the unburned and heat losses. In the case of a small boiler, the radiation loss was between 1 and 2% [23]. H_L was calculated using the following equation and is the sum of the lost enthalpies. In addition, it was reported that in the ASME power test code, the smaller the boiler size, the larger the heat dissipation loss was. The heat dissipation loss value used in this experiment was 1.5% the amount of heat input, and the design margin was 1%. The boiler efficiencies were 86.23%, 86.30%, 87.27%, and 87.27%, and as the blending ratio increased from 100/10 (coal/livestock waste) to 70/30 (coal/livestock waste), the boiler efficiency slightly increased, but it was confirmed that it did not have a significant effect.

$$\text{Combustion efficiency } (\%) = \left(1 - \frac{B_L}{HHV}\right) \times 100 \quad (1)$$

$$\text{Boiler efficicncy } (\%) = \left(1 - \frac{(H_L + B_L)}{HHV}\right) \times 100 \quad (2)$$

H_L is as follows:

$H_R = H_C(\text{Fuel combustion}) \times 1.5\%$

$H_{(H,M,F,S,B,G)} = m_{(H,M,F,S,B,G)} \cdot C_{P,\,(H,M,F,S,B,G)} \cdot dT$

$H_D = H_C(\text{Fuel combustion}) \times 1.0\%$

Table 4. Heat balance.

	Coal/Livestock Waste (100/0)	**Coal/Livestock Waste (90/10)**	**Coal/Livestock Waste (80/20)**	**Coal/Livestock Waste (70/30)**
Fuel combustion (H_C) [kcal/kg]	5085	4839	4628	4421
Unburned loss (B_L) [kcal/kg]				
$CO \rightarrow CO_2$	8.81	7.28	8.08	4.55
$CH_4 \rightarrow CO_2 + H_2O$	9.26	8.78	8.37	7.98
Unburned carbon $\rightarrow CO_2$	39.6	30.4	11.1	25.0
Combustion efficiency by HHV	98.87%	99.04%	99.64%	99.71%
Heat loss (H_L) [kcal/kg]				
Radiation loss (H_R)	76.28	72.59	69.42	66.32
Fuel Hydrogen latent heat loss (H_H)	155.21	156.83	149.64	151.10
Fuel Moisture latent heat loss (H_M)	195	198	201	204
Coal specific (H_F)	1.859	1.859	1.859	1.859
$CaCO_3$ calcination heat (H_S)	−9.64	−9.88	−10.22	−12.12
Bed ash drain (H_B)	5	6	7	8
Gas out of A/H (H_G)	183	157	124	102
Design margin (H_D)	51	46	46	44
Boiler efficiency by HHV	85.94%	86.00%	86.93%	86.94%

4. Conclusions

1. The temperature change of the rear equipment of the boiler according to the blending ratio was 100/0 (coal/livestock waste) to 70/30 (coal/livestock waste), and as the blending ratio increased, the temperature of the loop seal and the cyclone outlet decreased from 600 °C to 450 °C. The reason for the decrease in the cyclone outlet and the loop-seal temperature is that the circulated ash decreased and the supply of heat sources to the cyclone and loop-seal decreased. However, the reason there was no change in the temperature difference at the economizer outlet and bag filter is that in the economizer and bag filter, convective heat transfer by combustion gas acts as the main heat source and is less affected by the scattered ash.
2. Compared with bituminous coal combustion, the co-combustion of the livestock waste fuel increased the content of fixed carbon, which reduced the unburned carbon by approximately 10% from 39.68 wt.% to 28.51 wt.%; ash was increased by approximately 15% from 9.14 wt.% to 15.18 wt.%, which was expected to reduce the temperature of the boiler sand layer. However, the experimental results showed that there was no change in the combustion pattern according to the difference in the blending ratio.
3. The concentration of HCl was 3.45 ppm in the bituminous coal burning experiment and increased from 3.51 to 5.27 ppm as the blending ratio increased. On the other hand, it was shown that the conversion rate of HCl decreased from 0.45% to 0.04% as the blending rate increased. This phenomenon occurs because, when compared with the 0.02 wt.% of HCl content of bituminous coal, the HCl content of the livestock waste fuel was high at 0.63 wt.%, resulting in an increase in the HCl content of 0.02 to 0.25 wt.% in the blended fuel.
4. The results of the experiments on the bituminous coal burning and livestock waste fuel showed that the combustion efficiency and boiler efficiency of the bituminous coal combusting experiment and the blended livestock waste fuel experiment showed a pattern that slightly increased, such as combustion efficiency, but did not show a significant change. As a result, the co-combustion of coal and livestock waste fuel caused a change in the internal temperature of the combustor, but the supplied livestock waste fuels were fully combusted in the combustor, and the increase in the ratio of blended combustion did not affect the combustion and the boiler efficiency.

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