

Combustion Characteristics of Solid Refuse Fuels from Different Waste Sources

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Abstract: In the production (as co-fuel or alone) of solid refuse fuel (SRF), knowledge about the characteristics of the raw materials is required for an eco-friendly and effective combustion process. SRFs are commonly produced by drying combustible waste and removing incombustible matter, resulting in a higher combustibility as compared to the original waste. However, the characteristics of SRFs may highly vary depending on where and from which materials they were produced. Thus, we investigated the characteristics of various SRFs using thermogravimetric analysis (TGA). As a TGA sample is commonly small, on the scale of milligrams, and, unlike homogeneous fuels, SRFs are heterogeneous, individual SRF samples analysed with this method may not represent the bulk material, and sample properties may vary significantly between batches. Therefore, we further performed combustion experiments using a small-scale combustor and sample sizes from 1 to 10 g. To optimise SRF combustor design and determine the SRF characteristics, proximate, elemental, heating value, TG, and differential thermogravimetric analyses were conducted, and weight losses and gas concentrations at different temperatures were measured upon combustion. The lower heating values of the three analysed SRFs were 20,976, 16,873, and 19,762 kJ/kg, and their Cl contents were 0.89, 0.95, and 1.27 wt.% (legal criterion [Cl] < 2.0 wt.%). TGA and small combustor experiments showed that complete weight loss was achieved below 500°C. However, CO was detected until 620°C.

Keywords: Solid refuse fuel; small-scale combustor; thermogravimetric analysis; waste; gas concentration

1 Introduction

Recently, waste disposal has become problematic worldwide. This is because China, which had imported waste from around the world, announced in 2017 that it would no longer import waste, terminating such imports from January 2018. As detailed in the Chinese announcement, the waste import amount in 2016 was 7,300,000 tons of waste plastic and 2,700,000 tons of wastepaper. South Korea also exported 280,000 tons of waste plastics to China in 2017. Thus, South Korea, as well as other countries, now has to process its own waste.



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Over the past 20 years, combustible municipal waste has been incinerated, and the volume of this waste has been successfully reduced because of government action. Since 2008, technology to effectively recover heat from incinerators has been developed because of the rapidly increasing price of fossil fuels. Because technologies to recover energy from waste can replace fossil fuels and significantly reduce greenhouse gas emissions, research into the development of these technologies has been increasing [1,2]. Moreover, to utilise the heat generated from waste incinerators more efficiently, the Ministry of Environment has implemented policies focusing on the eco-friendly treatment of combustible waste, as well as the utilisation of heat energy. Currently, domestic solid refuse fuel (SRF) is produced by reducing the moisture and incombustible matter content of combustible waste in accordance with laws revised in 2013, and SRF products with improved combustibility are now being produced.

The previously produced four types of fuel, i.e., SRFs refused plastic fuel (RPF), refuse-derived fuel (RDF), tyre-derived fuel (TDF), and wood chip fuel (WCF), have been integrated into two types (RPF, RDF, and TDF as SRF and WCF as Bio-SRF), and SRF is now being produced in both moulded and non-moulded forms. In recent years, sewage sludge has been added to the SRF [3,4].

In South Korea, which imports significant energy from overseas because of its lack of fossil energy resources, it is necessary to develop and supply renewable energy for energy security. The production of renewable energy has increased year-by-year, accounting for 4.8% of the domestic energy production in 2016. Energy generated from waste represents 62% of the domestic renewable energy production, making it the most significant renewable energy source. Furthermore, because of the restrictions on the export of waste, it is necessary to utilise waste that had previously been exported overseas as a renewable energy source.

Technologies to recover energy from waste and waste biomass include co-firing of coal and SRF [5–8], torrefaction [9,10], co-firing of coal and biomass [11,12], gasification [13], pyrolysis [14], and SRF combustion [15–17]. In the past, energy was recovered by directly incinerating waste and waste biomass. However, combustion technologies that improve the efficiency of energy recovery from SRFs by improving their quality via processing are now being actively studied. In these combustion technologies, the SRFs are burned in combination with other fuels or on their own in power generation facilities that typically use large amounts of fossil fuels [10]. However, when coal, the existing fuel, is burned together with SRFs with different characteristics and fuel properties, problems in boiler operation can occur because the combustor design is based on coal combustion, and the burning of SRFs may exceed the operating parameters of the combustor. In addition, for SRF combustors, where the steam temperature is increased for steam power generation, damage to facilities may occur because of the high-temperature corrosion and local heating of the inner walls of the combustor and heat transfer devices. To address these problems, many researchers have conducted studies on the combustion characteristics of SRFs, such as slagging and fouling inside boilers, as well as flame stability [18–20].

For the combustion of SRFs in combination with other solid fuels or alone, the SRF characteristics must be known. In particular, Cl and S in SRFs can form melting compounds, such as NaCl, CaCl₂, KCl, Na₂SO₄, K₂SO₄, and MgSO₄, during the combustion process, causing high-temperature corrosion on the inner walls of the combustion chamber and heat transfer devices. Therefore, the S and Cl content should be as low as possible. To date, the combustion characteristics of fuels and waste have been investigated through thermogravimetric analysis (TGA) [21–24]. In the case of TGA, however, the amount of sample required in the analysis is very small, usually on the scale of milligrams. Therefore, while homogenous samples, such as coal, are representative for the bulk material, small samples of heterogeneous materials, such as combustible waste or SRF, are often not representative of the bulk sample. To address this problem, we have investigated the combustion characteristics of SRF samples slowly increasing the sample size from 1 to 10 g in a small-scale combustor.

In this study, to obtain the furnace operating parameters for the combustion of SRFs and to design a combustion boiler for SRFs, proximate analysis, elemental analysis, heating value measurements, TGA, and differential thermogravimetric analysis (DTG) were conducted. In addition, an experiment on the combustion characteristics was performed using a small combustor, and the concentrations of gaseous components, such as CO, NO, SO₂, and O₂, were measured to assess the basic pyrolysis and combustion characteristics of the SRFs.

2 Experimental Method and SRF Samples

2.1 Small-Scale Combustion System for SRF and Analysis Method

Fig. 1 shows the small-scale combustor for the SRFs used in this study. The combustor can be used to measure the weight loss during the combustion of the SRF sample, those weight was varied from 1 to 100 g. The maximum temperature of the electric furnace was 1,100°C, and the heating rate was 1–20 °C/min. The device consisted of a control box containing a gas analyser and a combustion device. The small combustor was equipped with a flow path on the top of the heat block cap, through which a certain amount of the SRF sample was injected and the air for combustion was supplied, as well as a sampling probe that could measure the gaseous pollutants after combustion. Under the heat block cap, an electronic scale was installed to measure the weight loss of the SRF sample upon combustion.

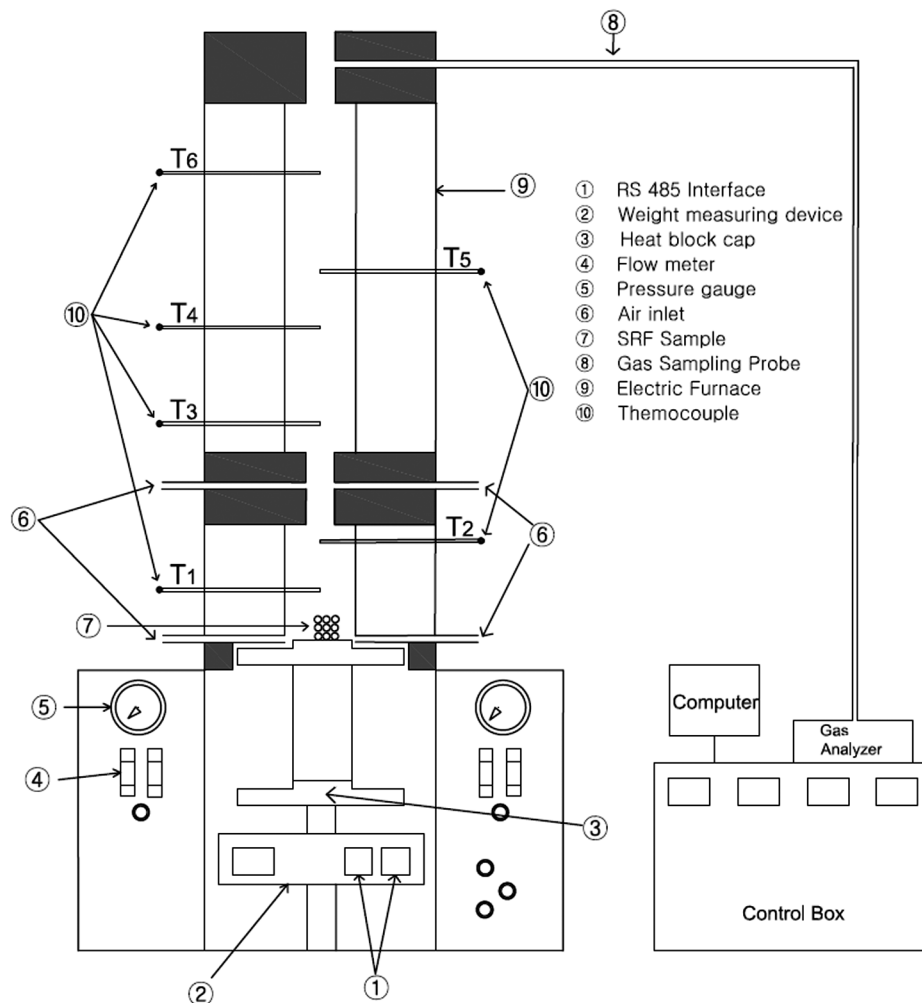


Figure 1: Small scale combustion system for SRFs

The air was evenly supplied through four positions, two positions on the left and two on the right side. In addition, air was supplied at a rate that the oxygen concentration did not change during the combustion process. The temperatures inside the combustor were measured at six positions (T1–T6), including two positions (T2 and T5) used for controlling the combustor temperature and four positions for measuring the gas temperature. The position of the thermometer used for measuring the weight loss and producing the concentration graph was at T4. The temperatures were measured using K-type thermocouples.

A EUROTRON (Greenline MK2) gas analyser was used to measure the O₂, CO, NO, and SO₂ concentrations continuously. TGA is a method of measuring and analysing the change in the weight of a sample with temperature change. The analytical instrument used in this study was a TGA/DSC1/1600 LF (Mettler Toledo). Proximate analysis was carried out using a TGA-701 from LECO Co., USA, elemental analysis was carried out with a 1112 elemental analyser from Thermo-Fisher, heavy metal analysis was carried out with an ICAP 6000 from Thermo Elemental, and the lower heating values were obtained using a 1261 EA.

2.2 SRF Samples

RDF, RPF, and TDF, which are existing solid fuel products, were integrated into SRFs, and WCF was transformed into Bio-SRF. The waste used for SRF production included municipal waste, waste synthetic fibres, waste tires, waste synthetic resins, rubber, and bio-solid fuel products. Because the production of SRFs requires many raw materials, it is very difficult to produce SRFs with consistent quality; thus, the quality varies significantly.

Moreover, non-moulded products applied only to refuse derived fuel (RDF) were also applied to SRFs and Bio-SRF. The same quality regulation criterion applies to moulded and non-moulded SRFs, except for moisture: the maximum moisture content should be 25.0 wt.% for non-moulded SRFs and 10.0 wt.% for moulded SRFs. For SRFs, the lower heating value should not be lower than 14,654 kJ/kg and the ash content not exceed 20.0 wt.%. The Cl and S contents should be 2.0 wt.% and 0.6 wt.% or lower, respectively. Concerning heavy metals, the maximum mercury, cadmium, lead, and arsenic contents should not exceed 1.0, 5.0, 150, and 13.0 mg/kg, respectively. The sample size should not exceed 50 × 50 mm (width × depth) but can be 120 × 120 mm when SRFs are manufactured on the same site for direct use. The SRFs used in this study were SRF-1, SRF-2, and SRF-3, which were manufactured in different factories.

2.3 Results of Proximate and Ultimate Analysis

Tab. 1 and 2 show the results of the proximate and ultimate analyses of the three SRF samples, respectively. The moisture content was 11.2 wt.% for SRF-1, 10.0 wt.% for SRF-2, and 1.7 wt.% for SRF-3; thus, SRF-3 had the lowest moisture content. The fixed carbon contents were 6.8, 14.1, and 11.7 wt.% for SRF-1, SRF-2, and SRF-3, respectively, while the volatile matter contents were found to be 69.6, 66.9, and 75.1 wt.%, respectively. Because various waste materials, such as vinyl, plastics, and styrofoam, are included in the SRF manufacturing process, the content of each component varies significantly depending on the SRF manufacturer, sample collection, and the season. Moreover, the moisture content differs depending on the waste storage method. The lower heating values of the three SRF samples were 20,976, 16,873, and 19,762 kJ/kg. Thus, the range of lower heating values was large and depended on the type of combustible waste material contained in the SRF.

The fuel ratios (fixed carbon [FC]/volatile matter [VM]) were 0.10, 0.21, and 0.16, as listed in Tab. 1, and the C/H ratios were 7.16, 7.47, and 7.36, as listed in Tab. 2, indicating that the three SRFs are similar. An increasing C/H ratio may increase the amount of soot produced during combustion. For comparison, the fuel ratio of anthracite is 12 and that of lignite is 1 or less. The C/H ratio of coal ranges from 10 to 30 and that of gaseous fuel is approximately 3. For SRFs, the fuel ratio is very low (1 or less) and the C/H ratio is low (10 or

Table 1: Proximate analysis of the SRFs

Sample	Water (wt.%)	Ash (wt.%)	Volatile matter (wt.%)	Fixed carbon (wt.%)	Fuel ratio (FC/VM)	Low heating value (kJ/kg-wet)
SRF-1	11.2	12.4	69.6	6.8	0.10	20,976
SRF-2	10.0	9.0	66.9	14.1	0.21	16,873
SRF-3	1.7	11.5	75.1	11.7	0.16	19,762

Table 2: Ultimate analysis of the SRFs

Sample	C (wt.%)	H (wt.%)	N (wt.%)	O (wt.%)	S (wt.%)	Cl (wt.%)	C/H
SRF-1	65.37	9.12	0.93	23.49	0.20	0.89	7.16
SRF-2	50.71	6.79	3.35	37.56	0.64	0.95	7.47
SRF-3	53.14	7.22	3.60	34.04	0.73	1.27	7.36

less). This is because the fixed carbon content is low, and the volatile matter content is high for the three samples. This results in early ignition or a shorter combustion duration. As shown in [Tab. 2](#), the chlorine contents were 0.89, 0.95, and 1.27 wt.%. The chlorine content of municipal solid waste (MSW), which is the raw material in the SRFs varies with the season and collection site. The legal criterion for chlorine content in SRFs is 2.0 wt.% or less. If the chlorine content is 0.5 wt.% or less, the quality of the SRF is excellent. If the Cl content is high, though, HCl and Cl₂ gases are emitted during combustion, and dioxin can also be discharged. In addition, the Cl component also affects combustibility because it can act as a flame suppressant during combustion.

[Tab. 3](#) shows the heavy metal analysis results for the three SRF samples. A mercury content of 0.01 mg/kg was found for all three samples, and arsenic was not detected. All three SRF samples, thus, met the criteria for mercury, cadmium, lead, and arsenic contents.

Table 3: Heavy metal analysis of the SRFs

Sample	Hg (mg/kg)	Cd (mg/kg)	Pb (mg/kg)	As (mg/kg)
SRF-1	0.01	1.7	25.9	ND
SRF-2	0.01	0.3	ND	ND
SRF-3	0.01	0.3	2.0	ND
Regulation quality	<1.0	<5.0	<150.0	<13.0

3 Results and Discussion

3.1 TGA Results

TGA has been widely used to investigate the thermal stability and change of state of materials on heating. Physical and chemical changes in the samples can be understood by observing the weight change of a sample during heating, and the weight change can be used to understand the phenomena induced by heating. In addition, the burning rate according to the temperature interval can be found from the DTG graph. In TGA, there are three main steps. The first step is drying, the second step is devolatilisation, and the third step is the char combustion process.

Fig. 2 shows the TGA results used to determine the combustion characteristics of the SRFs. Air was used as the carrier gas, and the heating rate was 10 °C/min. The maximum temperature was 800°C. For SRF-1 and SRF-2, which had a high moisture contents, the weight began to decrease at 100°C. For SRF-3, which had a low moisture content, the weight began to decrease at 200°C. At temperatures between 200 and 500°C, the initial volatile matter, carbon, and residual volatile matter were discharged and combusted. In general, adherent moisture is evaporated at temperatures up to 150°C, and the devolatilisation reaction occurs at 200 °C or higher. A sharp weight loss occurred between 200 and 500°C. This is because of the depolymerisation reaction of polymers and the combustion of the volatile matter. For the SRFs used in this study, there was almost no weight loss above 500°C because decomposition had completed.

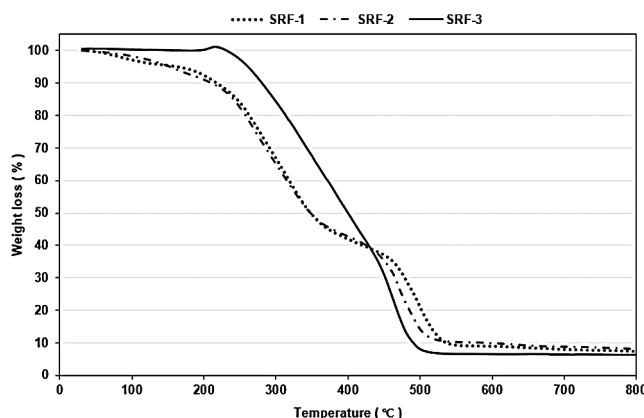


Figure 2: TGA curves for SRFs (heating rate: 10 °C/min, carrier gas: air)

Fig. 3 shows the DTG curves. The DTG curves show the weight loss change with temperature for each sample, more clearly showing the combustion characteristics. If the peak in the DTG curve is small, the weight loss change is small; if the peak is large, the weight loss change is high. The DTG curves contained two peaks at 300°C and between 480 and 500°C for both SRF-1 and SRF-2. For SRF-3, the first peak was at 200°C, and the highest peak occurred at 470°C. This indicates that SRF-1 and SRF-2 contained similar waste materials, whereas SRF-3 contained different types of waste. According to the results of the TG/DTG analysis, the combustion characteristics of SRFs were different from those of anthracite. When the reaction had been completed, the combustion characteristics of the SRFs were similar to those of biomass, such as wood pellets [22–23].

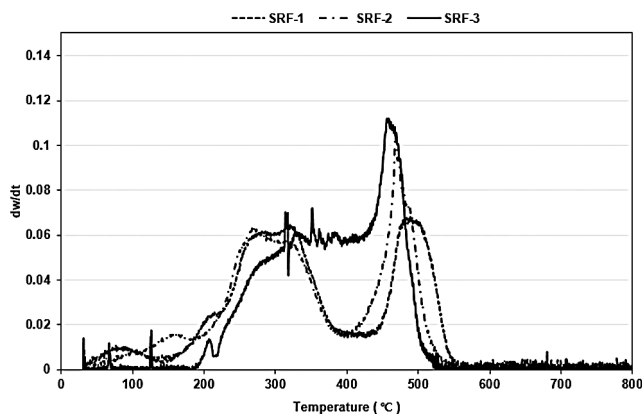


Figure 3: DTG curves for SRFs (heating rate: 10 °C/min, carrier gas: air)

3.2 Results of the Small-Scale Combustor Experiments

Fig. 4 shows the weight loss of the SRF samples obtained from experiments in the small-scale combustor. Compared to the TGA results shown in Fig. 2, the combustion reaction started early, and the temperature at which decomposition was completed was lower. In the TGA experiments, the reaction was completed at approximately 500°C for all three SRF samples. In the small-scale combustor, however, the reaction was completed at 380°C for SRF-2 and SRF-3 and at 470°C for SRF-1. The combustion reaction began at a lower temperature in the small scale combustor compared to that in the TGA experiments. This appears to be because of the small TGA sample size, indicating that there was no delay in heat and mass transfer. The thermal decomposition of the combustible materials in the SRFs, such as wood, paper, plastics, and fibres, is a complex decomposition process in which chemical chain reactions occur. In such decomposition reactions, radical species dominate the chain reaction. It appears that the start and end temperatures of the combustion reaction in the small-scale combustor were lower than those in the TGA measurements because chain reactions induced by radicals, generated in the early stages of combustion occurred, and, thus, the chemical reaction proceeded earlier. Therefore, if the burning rate obtained from TGA is utilised to design a combustor, errors may occur in the calculation of the solid residence time for complete combustion. It is, thus, crucial that this difference is considered in combustor design.

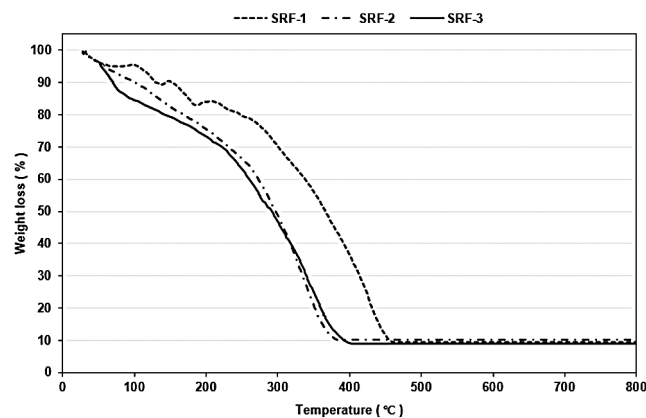


Figure 4: Reaction curves for SRFs in the small-scale combustor (heating rate: 10 °C/min, carrier gas: air)

Fig. 5 shows the weight loss of SRF-1 tested in the small combustor and the concentrations of CO, NO, SO₂, and O₂ measured at the same time. The O₂ concentration remained at 21% from the beginning to the end of the experiment. The combustion of the SRF sample was performed when the O₂ concentration was sufficiently high to be unaffected by the combustion reaction. The CO, NO, and SO₂ concentrations are relative values for comparison and were not corrected using the O₂ concentration. All three combustion gases were detected above 250°C. In the SRF-1 combustion experiment, SO₂ was produced in the highest concentration at 330°C but was not detected above 450°C. NO was produced in high concentrations at 340 and 430°C and was continuously emitted until 800°C. NO was generated from the N in the fuel (see elemental analysis in Tab. 1). CO was produced in the highest concentration at 370°C but was hardly generated above 620°C. As shown by the TGA weight loss curve in Fig. 2, no weight loss occurred above 500°C. However, in the combustor, CO and NO continued to be generated above 500°C until 620 °C, at which the highest weight loss occurred.

Fig. 6 shows the concentrations of CO, NO, SO₂, and O₂ for SRF-2. All three gases were detected above 250°C, as for SRF-1. The highest concentration of SO₂ was observed at 340°C, and SO₂ was not generated above 450°C. NO was produced in high concentrations at 370 and 500°C and was continuously emitted until 800°C. CO exhibited the highest concentration at 390°C and was hardly generated above 620°C.

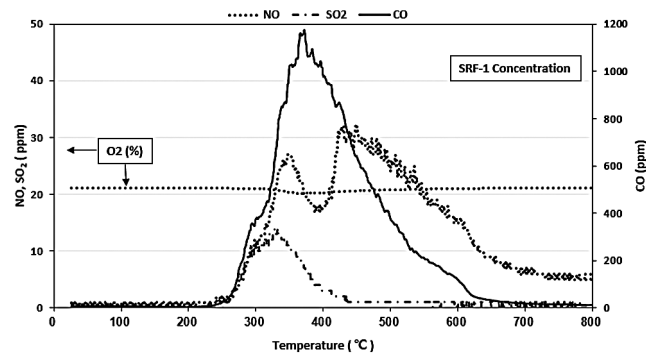


Figure 5: CO, NO, SO₂, and O₂ concentration curves for the SRF-1 in the small-scale combustor (heating rate: 10 °C/min)

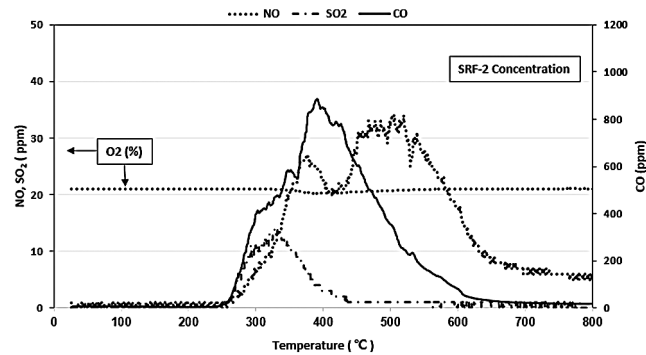


Figure 6: CO, NO, SO₂, and O₂ concentration curves for the SRF-2 in the small-scale combustor (heating rate: 10 °C/min)

Fig. 7 shows the concentrations of CO, NO, SO₂, and O₂ for SRF-3. All three gases were generated above 250°C in the same manner as for SRF-1 and SRF-2, but the concentrations highly differed. The concentration of SO₂ was higher than that of NO, and the highest concentration was observed at 450°C. NO was produced in the highest concentration at 450°C and was continuously generated until 800°C. CO showed a high concentration of 4,000 ppm at 450 and 480°C. These patterns were completely different from those of the other SRF samples.

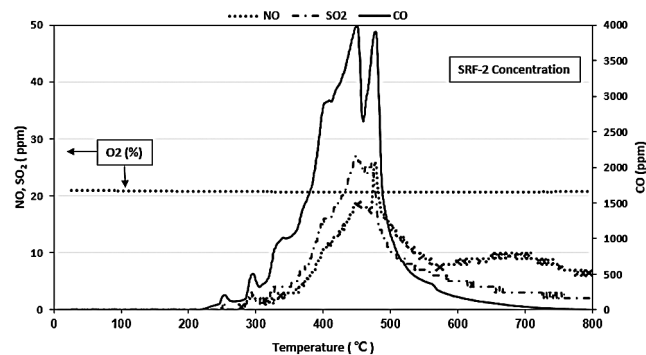


Figure 7: CO, NO, SO₂, and O₂ concentration curves for the SRF-3 in the small-scale combustor (heating rate: 10 °C/min)

4 Conclusion

To investigate the fuel characteristics of solid recovered fuels (SRFs) prepared from different waste materials, three types of SRFs manufactured by different factories were collected, and elemental, proximate, heating value, and thermogravimetric analyses were conducted. In addition, to observe the actual combustion characteristics of the SRF samples, weight loss experiments were performed, and the emitted combustion gases were analysed using a small-scale combustor. The results are summarised below.

The moisture contents of the three SRF samples were 11.2, 10.0, and 1.7 wt.%, demonstrating the large variation in moisture depending on the manufacturer. The fuel ratios (FC/VM) of these samples ranged from 0.10 to 0.21, and the C/H ratios were between 7.16 and 7.47. These results indicate that the three SRF samples contained a large amount of volatile matter, reducing the ignition and combustion time. Because of the possibility of an incomplete combustion due to the large amount of volatile matter, it is important to supply sufficient amounts of air and mix the gases well in the secondary combustion chamber for complete combustion.

The Cl content, which accelerates the generation of dioxin and the corrosion of metal devices in the combustor, ranged from 0.89 to 1.27 wt.%, which was lower than the SRF legal criterion of a maximum of 2.0 wt.%. However, it is necessary to reduce the Cl content to 1.0 wt.% or less for eco-friendly combustor operation.

The lower heating values of the SRF samples were 20,976, 16,873, and 19,762 kJ/kg, respectively, which were affected not only by the ash and moisture contents but also by the properties of the waste used.

According to the TGA results for the SRFs, the initial volatile matter, carbon, and residual volatile matter contents were discharged and the fixed carbon was combusted at temperatures between 200 and 500°C. In the SRF combustion experiments with the small-scale combustor, however, the weight loss occurred at lower temperatures than those observed in the TGA experiments, and the weight loss was terminated at 380°C for SRF-1 and SRF-2 and at 450°C for SRF-3.

CO, NO, and SO₂ were generated in the small-scale combustor above 250°C for all three SRF specimens. SO₂ was produced at the highest concentration between 330 and 340°C for SRF-1 and SRF-2 and at 450°C for SRF-3. NO was produced in high concentrations in two temperature ranges: 340–370 and 430–500°C for SRF-1 and SRF-2 and at 450°C for SRF-3.

CO exhibited the highest concentration in the temperature range of 370–390°C for SRF-1 and SRF-2 and 450–480°C for SRF-3. The highest CO concentrations for the SRF samples were 1,174 ppm for SRF-1, 884 ppm for SRF-2, and 3,985 ppm for SRF-3. The CO gas generated from incomplete combustion was continuously emitted, even above 500°C, at which the SRFs lost no further weight, but CO was hardly generated above 620°C.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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