

THERMAL ANALYSIS OF DIFFERENT REFUSE DERIVED FUELS SAMPLES

by

Gizem AYAS^a and Hakan F. OZTOP^{b*}

^aDepartment of Machine Programs, Vocational School, Mardin Artuklu University, Mardin, Turkey

^bDepartment of Mechanical Engineering, Technology Faculty, Firat University, Elazig, Turkey

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As a result of the activities carried out by people to maintain their daily lives in different places such as homes, hospitals, hotels or workplaces, waste consisting of furniture, paint, batteries, food waste, sachets, bottles, fabrics, and fibers with the heterogeneous structure is called municipal solid waste. Secondary fuels with higher heating value, which are generated by recycling of non-recyclable and reusable wastes in municipal solid wastes, are called as refuse derived fuel (RDF). In this study, RDF1 (taken in December, winter season) and RDF2 (taken in June, summer season) samples obtained from different dates were used. The ultimate, proximate, calorific value, X-ray fluorescence, thermogravimetric analysis, and differential scanning calorimetry were performed for these samples. Combustion characterization from RDF samples was investigated in the applied analyzes. The results of the content analysis made were examined separately and compared with the thermogravimetric analysis and differential thermal analysis combustion graph curves. It was revealed that the RDF1 sample had a better combustion compared to the RDF2 sample, as the ash amount and content obtained as a result of the combustion also supported other data. In addition, the results of the analysis show how different the RDF samples taken from the same region in two different months are different from each other.

Key words: *municipal solid waste, RDF, thermal analysis, fuel, differential scanning calorimetry*

Introduction

In parallel with technological developments in the world, global energy consumption is also gradually gaining momentum. Rapid population growth and a correspondingly rapid depletion of traditional energy resources encourage societies to use existing energy potential more effectively, while at the same time forcing them to find new sources of energy. In this context, energy producers must follow environmental rules. In this context, generation of municipal solid waste (MSW) tends to increase with the growing population and economic development of society. Therefore, establishing environmentally sustainable waste management strategies is crucial. In this sense, energy recovery strategies have come to the forefront as they increase the resource efficiency and replace the fossil fuels with renewable energy sources by providing material and energy-recovery instead of landfill disposal the wastes. The RDF, an alternative fuel produced from energy rich MSW materials diverted from landfills, is one of the strategies of energy gener-

* Corresponding author, e-mail: hfoztop1@gmail.com

ation from wastes that is getting more and more attention [1-5]. In short, RDF has higher heating value (HHV) and less pollutant emission values, is easy to store and transport and has greatly reduced the idle waste volume [6-9]. Chang *et al.* [10] evaluated the comparative effects by burning MSW and RFD in the same incinerator. They found that the incineration of RDF presents a relatively better performance in several aspects. Wagland *et al.* [11] performed an experimental work to compare the differences between MSW derived solid recovered fuel (SRF) and RDF. Consequently, they observed that emissions in flue gas and ash samples from the (coal + 10% SRF) fuel mixture were found lower than that obtained for coal + 10% RDF fuel mixture. Robinson *et al.* [12] made work on thermogravimetric analysis (TGA) to obtain a variety of materials prepared from a commercially available RDF using a variety of procedures. Applicability of the TGA method to the determination of the renewable content of RDF was considered. The main aim of the study by Akdag [13] was to investigate the thermal characteristics and co-combustion efficiency of two RDF samples in Turkey. They performed the proximate, ultimate, and TGA analysis for samples. In their analysis when RDF in the mixture was higher than 10%, the CO concentration in the flue gas increased and so the combustion efficiency decreased. Furthermore, the combustion characteristics changed from char combustion volatile combustion. Hou *et al.* [14] performed a study to estimate the heating value and combustion characteristics of densified RDF produced from oil sludge. They observed that the burning of wood powder as an ingredient is faster than that of coal powder. The experimental results improved the understanding of the application of RDF-5 and demonstrated the combustion characteristics of RDF-5 based on oil sludge. Fellner *et al.* [15] defined a technique to find the mass, energy, and carbon content of biogenic and fossil matter in RDF. They combined the technique standard chemical information about biogenic and fossil material with data from a chemical analysis of the RDF. They validated their method with the literature and developed a correlation. Myrin *et al.* [16] performed a study on the characterization of three different RDF which are produced from recovered wood and two MSW. They found that RDF with low food waste content has very favourable fuel quality and PCDD/F emissions. Ma *et al.* [17] studied the chlorine content in eight fractions of MSW. They investigated the influence of the operating temperature and fuel additives such as sulfur and silica on the volatilization of chlorine in the combustion process. Wangland *et al.* [11] made an experimental work to make a comparison of differences between MSW derived SRF (complying with CEN standards) and RDF. They indicated that the tested fuels can be used as alternative fuels in any industrial system. Marsh *et al.* [18] concerned with the production and properties of fuel pellets to use in energy from different waste technologies. They stated that such plants are likely to be utilised as future waste solutions for the UK and other countries to reach waste treatment targets. They also observed that the obtained pellet compressive strength was not significantly affected by extrusion conditions. Schwarzbock *et al.* [19] made a study to investigate the importance of preparation of species for RDF. Balance method was used by authors with this aim. In their method, different particle dimensions were studied in different millings procedure. After that elemental and base combustion analysis were performed. They showed that their method is acceptable when it is compared with literature. Jamradloedluk and Lertsatitthanakorn [20] produced the RDF with different raw materials such as sawdust, corrugated paper, plastic bag, and dry cooked rice, *etc.* The effects of the glycerin binder were tested and found to be an increase in the amount of dry cooked rice, and the addition of glycerin in the mixture led to an increase in density. In the study of Porshnov *et al.* [21], performance of RDF for pro-gasification and materials are produced in both Letonia and Estonia. They used TGA in their method and materials can be used for modern thermal technology systems and furnaces. Porshnov *et al.* [22] investigated the thermal degradation for RDF consisted of paper, wood, fiber and other

flammable materials by using TGA. They showed that there is big differences among waste components. At the end of the work, they presented their results in four steps for different phase changes. Nobre *et al.* [23] made an analysis on emission due to combustion of RDF without any dangerous or poison material. They warmed up to RDF species up to 300 °C and 400 °C for 30 minutes. At the end of analysis, they obtained CO₂ and CO as emission but CH₄ was occurred just for 400 °C. It can be obtained liquid materials during procedure. Yui *et al.* [24] investigated the heavy metals after combustion of RDF and made calculation using thermodynamics model. They analysed the flying ash behavior. Edo *et al.* [25] studied the emission after combustion of RDF, MSW, and construction waste.

The main aim of this study is to investigate the thermal analysis and fuel characterization of different RDF samples from different season and different month of the year by using experimental techniques. In this context, two RDF samples are obtained and their ultimate, proximate, calorific value, X-ray fluorescence (XRF), TGA, and differential scanning calorimetry (DSC) analysis were performed for these samples. The study shows the effects of season and different month of the year on combustion characteristics of RDF. This study will help to readers on combustion of RDF samples with organic wastes which collected from different areas. Thus, this result can help to get energy in rural area to reduce transport costs.

Material and method

Two different RDF examples were used in the present study and they were taken from energy recovery facilities at Turkey in different months. The RDF2 and RDF1 species were obtained on June 2017 and December 2017, respectively. Experiments were done in the same year. These samples had a coarse-grained structure when they arrived at the laboratory. Therefore, the RDF1 specimens were kept at 75 °C for two days in order to bring the samples to the size appropriate for analysis. It was then passed through three kinds of grinders as rough (2 cm), intermediate (0.5 cm), and blade (0.1 cm). In this way, the components in the fuel matrix have been made as homogeneous as possible. In addition, the samples prepared as 20 mg were pressed to obtain 5 mm diameter pellets for better measurements and more samples to fit into TGA containers before the TGA analysis. The TGA analysis were performed by using these pelleted samples.

The proximate, ultimate, calorific values and XRF analyzes were performed on RDF samples brought to the appropriate size and homogeneity. All analyzes were repeated three times to check the accuracy of the analyzes and sample homogeneity.

As a result of proximate analysis, the percentage of moisture, ash and fixed carbon content of the waste components was determined experimentally, and the percentage of volatile matter content was calculated numerically. That is, the fixed carbon was calculated by subtracting the percentage of the volatile matter and ash content from the percent of the total on a dry basis. Moisture content was determined by the ASTM E790-08 method in the analysis. Then, the volatile matter and ash content were determined by ASTM E897-88 and ASTM E790-08 methods, respectively.

The ultimate analysis was carried out with the Leco CHNS-932 analyser at Inon-u University

Scientific and Technological Center Research Laboratory, Turkey. Chemical elements in the fuel matrix is determined by elemental analysis. The chemical elements determined give us information about combustion reactions. The main chemical elements in fuel are: C, O, H, N, and S. The C, H, N, and S percentages of fuel components were determined by the device. The amount of oxygen was calculated numerically.

The HHV of samples for RDF1 and RDF2 was determined by using JULIUS PETERS 11350 BERLIN adiabatic calorimeter. The analysis was carried out at the Chemical Engineering Department Laboratory of Firat University, Elazig, Turkey. The HHV are determined according to ASTM method E711-87. The results of the analysis were taken after the device is calibrated.

It is well known that the heating value is one of the basic parameters for determining the combustion properties of the fuel. This value is expressed in two ways as HHV and lower heating value (LHV). As a general definition, the definition of the HHV is the heat energy released when the water formed in a combustion reaction is in the liquid phase. The HHV of the samples were obtained as a result of the analysis. The lower LHV can be defined as the heat energy released when the water formed in a combustion reaction is in the vapor phase. The LHV of the samples were calculated using the HHV obtained from the bomb calorimeter from [26]:

$$LHV_{\text{moist}} = HHV_{\text{moist}} \times \frac{100 - W}{100} - 24.42 \quad (1)$$

The XRF analysis was carried out using a PANalytical AXIOS ADVANCED device at Erciyes University Technology Research and Application Center, Kayseri, Turkey. This analysis was performed to determine the content in the ash. The data obtained were used to calculate the impurity and slagging index of the RDF samples.

The majority of the content of RDF is paper and plastic fraction. This means that the boilers have ash content which can lead to contamination and corrosion of the boilers and which may adversely affect the quality of the gas emitted. Bad conditions such as corrosion and contamination can occur inside the combustion plants and they cause the failure of this plant. Thus, they can increase the damage inside the boiler. They cause major damage during the process, as well as large losses in heat transfer and reduce system efficiency. There are two important factors that cause these damages, such as slag formation and contamination in boilers. The slag formation is the formation of ash deposits in the refractory chambers of the part which is resistant to high temperatures due to the molten ashes. Contamination occurs in the heat transfer zones of the boiler and consists of ash deposits during the cooling of the gases. This reduces boiler efficiency as previously mentioned and causes the system to pause over time. Therefore, information on the ash content and calculation of pollution rates have an important role in the development of the RDF. Thus, the XRF analyser was used in ash content analysis. In this study based-acid ratio, B/A, and sulfur ratio, Rs, for slag formation indexes, total alkalis, TA, and impurity index, Fu, for contamination factor were calculated. It is assumed that the basic compounds present in the ash reduce the melting temperature, while the acidic compounds are assumed to increase. The Rs is related to the potential for slag formation [27]. The value ranges of these factors are given in tab. 1.

Table 1. Limit values of slag formation and contamination indices [27-30]

	Limit values			
	Low	Medium	High	Extreme high
Sulfur ratio, <i>Rs</i>	< 0.6	0.6-2.0	2.0-2.6	>2.6
Impurity index, <i>Fu</i>	≤0.6	0.6-1.6	1.6-40	–
Base-acid ratio, <i>B/A</i>	<0.5	0.5-1	>1	–
Total alkalis, <i>TA</i>	<0.3	0.3-0.4	>0.4	–

Table 1 [27-30] shows the limit values of slag formation and impurity indexes. As a result of the analysis, comments were made according to these value ranges. Equations (2)-(4) were applied by looking at the values in the results and index results were obtained [31]. A comparison was then completed and appropriate comments were made. When the chlorine content was examined according to the standards, the limit value was 1. In order to be used as fuel, the produced ATY must be $Cl \leq 1$ [32]:

$$B / A = \frac{Fe_2O_3 + CaO + MgO + K_2O + Na_2O + P_2O_5}{Al_2O_3 + SiO_2 + TiO_2} \quad (2)$$

$$Rs = (B / A) \times S \quad (3)$$

$$TA = Na_2O + K_2O \quad (4)$$

$$Fu = (B / A) \times (Na_2O + K_2O) \quad (5)$$

The TGA analysis was used as a function of time and temperature. The determination of the losses or gains in the mass of a continuous sample can be done in this way. The sample to be used in the experiment was heated at a constant heating rate and the mass change was measured and recorded as a function of temperature. Changes in the mass of the sample as a function of temperature and the intervals at where these changes are spread are an indication of the thermal stability of the sample. Therefore, TGA analysis was performed and the thermal characteristics of the samples were investigated. The analysis was carried out using a Perkin Elmer Pyris TG/DTA instrument in the Physics Department of Firat University Science and Literature Faculty. The analysis was performed at a heating rate of 10 °C per minute, a gas-flow of 40 °C per minute, and a temperature between 20 °C and 1000 °C. As a result of the analysis made, TGA and DTG curves of RDF1 and RDF2 samples were obtained.

The differential scanning calorimeter (DSC) measures the amount of energy absorbed or released while the sample is heated, cooled, or maintained at a constant temperature. As a result of this method, the temperature difference between the reference and the sample is indicated by time or temperature. The DSC analysis was carried out to obtain a clearer view of the DTA curves of the samples and to determine the combustion temperatures of up to 500 °C. The analysis was performed on the Hitachi DSC 7010 instrument in the Mechanical Engineering Department of Firat University. First, the instrument calibration was checked with a known sample and then the analysis was initiated. The analysis was carried out at a heating rate of 10 °C per minute, a gas-flow of 40 °C per minute and temperature values were ranging between 20 °C and 500 °C.

Results and discussion

In this study, two samples, which are called as RDF1 and RDF2, were examined. The results of the present study are given clearly under the following headings. The comparison of the different RDF samples used in the study and the literature are given in tab. 2. This analysis determined the volatile matter, ash content and fixed carbon content of RDF samples. In this study, the volatile matters of RDF samples for RDF1 and RDF2 were 68.91% and 56.05%, respectively. Moreover, the ash contents for RDF1 and RDF2 were 22.06% and 31.89%, respectively. Table 2 shows that the RDF1 has a lower ash content and higher volatile content than the RDF2. Also, the moisture content of RDF2 more than that of the RDF1. Since the RDF1 sample was produced in winter conditions, an additional drying process was applied. The reason for the

high ash percentage of the RDF2 sample. It is due to the fact that components such as paper that support the ash formation are predominant [13]. When all these analysis results are compared with the literature, it is seen that it is within the value range in the literature. Calorific value analysis results are also given in tab. 2.

Table 2. Proximate analysis results of RDF1 and RDF2 samples and comparison with the literature [13, 33-37]

	Moisture [%]	Volatile matter [%] ¹	Fixed carbon [%] ¹	Ash content [%] ¹	Low heating value [kJkg ⁻¹] ²
Literature ³	2-17-48	19-76-90	3-5-21	7-15-59	10969.41-25916.29
RDF1	3,30	68.91	5.73	22.06	19134.13
RDF2	3,50	56.05	8.76	31.89	13894.44

¹ % by weight on dry basis; ² Lower heating value on dry basis [kJkg⁻¹]; ³ The low number indicates the minimum value observed in the literature, the high number indicates the maximum value observed, and the middle number indicates the average of the observed values;

Analysis of calorific value analysis, tab. 2, the obtained results showed that the heating value results of RDF samples are compatible with the literature. As shown in tab. 2, the HHV belongs to the RDF1 sample. The elemental analysis showed that the high carbon content was also found in the RDF1 sample. This is because the heating value is proportional to the amount of carbon given in RDF [38]. The heating value of the RDF1 sample is considerably higher than the heating value of the RDF2 sample. This is because the concentration of organic matter and plastic material in the fuel matrix of the RDF1 sample is dominant. The elemental analysis results are given in in tab. 3.

Table 3. Elemental analysis results of RDF1 and RDF2 samples and comparison with the literature [13, 26, 32, 33, 39]

Sample	Carbon [%] ¹	Hydrogen [%] ¹	Nitrogen [%] ¹	Sulfur [%] ¹	Oxygen [%] ²
Literature ³	24-44-58	1-5-8	0.04-0.97-4	0-0.46-1.50	17-36-44
RDF1	36.15	5.01	1,92	0,47	35
RDF2	19.30	5.04	2.37	0.44	40.96

¹ % by weight on dry basis; ² determined from the difference; ³ maximum, minimum and average value range observed in the literature is in wt.%

The C, H, N, S, and O amounts of fuels obtained in element analysis and the literature are given in tab. 3. Elemental analysis results of the samples show that RDF consists mainly of C and O. Looking at tab. 3, it is seen that the amount of C does not exceed 37% and that of O amount does not exceed 41%. When looking at the other elements in the fuel matrix for RDF samples, it is seen that H and S amounts are very close to each other and their amounts do not exceed 6%. When N amounts are analyzed, it is seen that RDF1 sample has less N amount compared to RDF2 sample. This indicates that RDF2 sample will emit a more polluted gas than RDF1 sample [13]. When tab. 3. is analyzed to compare with the literature, it is seen that RDF1 sample is compatible with the literature data, while RDF2 sample is only C amount lower than the literature. The XRF analysis results are given in tab. 4. The table also shows the ash contents for RDF1 and RDF2 samples. All values calculated from the equations for slag formation are given in tab. 5.

It was found that the slag formation and contamination indices of RDF1 sample had high B/A, Rs, TA, and Fu ratios. When the RDF2 sample was examined, it was observed that B/A ratio was moderate, Rs ratio was low, TA and Fs ratios were high. Looking at these two

Table 4. The XRF analysis results [wt.%]

	RDF1	RDF2
CaO	10.34	10.25
Fe ₂ O ₃	1.28	1.794
SiO ₂	1.66	12.25
Cl	0.92	0.663
SO ₃	0.84	0.302
Al ₂ O ₃	0.79	3.420
K ₂ O	1.28	1.157
TiO ₂	0.44	0.397
Na ₂ O	0.91	0.564
P ₂ O ₅	0.32	0.992
MgO	0.30	0.724
ZnO	–	0.080
CuO	–	0.048
MnO	–	0.035
PbO	–	0.010
BaO	–	–
SrO	–	0,025

Table 5. Slag formation and contamination indices

		RDF1	RDF2
Slag forming indices	B/A	4.99	0.96
	Rs	2.32	0.42
Pollution indexes	TA	2.19	1.71
	Fu	7.18	1.61

RDF samples, when we compare the ash content of RDF1 and the ash content of RDF2, the RDF2 sample was a cleaner waste. However, the rates were higher than normal. Improving these factors will increase system efficiency and extend the life of the plant. Therefore, these values must be taken into account for fuels.

As shown in tab. 4, the Cl content of RDF1 and RDF2 samples does not exceed the limit value but is very close to the

limit. In this result, the main problem for chlorine in RDF samples especially for RDF1 is the presence of PVC pieces, plastics and paper. Also, some organic wastes such foods give same result [17, 40, 41]. As a result, RDF samples tend to form contamination and slag. Akdag *et al.* [5] stated that these rates may vary according to RDF content in their studies and that some precautions should be taken to prevent this.

The thermal properties of the samples were investigated by TGA analysis. In this study, RDF1 and RDF2 samples were analysed by using TGA. The TGA and DTA curves of the samples were also obtained as shown in fig. 1.

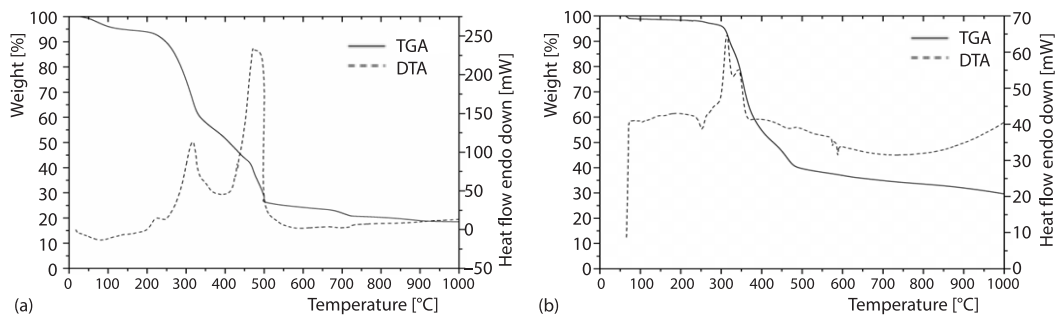


Figure 1. The TGA and DTA curves of the RDF1 (a) and RDF2 (b) samples

It is seen that there are mass losses in four different regions from the fig. 1(a). The phase transformations on the DTA curve of the reactions causing each mass loss are visible. In the first zone (0-200 °C), it is seen that moisture output from the RDF sample and the first mass loss occurs. In addition moisture, it is important to note that a small amount of volatile

material can escape. After this region, three exothermic reaction peaks were observed from the DTA curves and these peaks were the result of one combustion reaction. In addition, large mass losses were obtained in the TGA curve when these combustion reactions occurred. In this region, some materials in RDF1 whose combustion temperature was reached, burned and caused mass losses. After these severe combustion reactions, *i.e.* after the temperature exceeds 600 °C, a small mass loss was observed in the values. Argawal [42], Cozzani *et al.* [43], and Skodras *et al.* [44] stated that two large peaks will occur when the RDF sample is subjected to combustion. They also emphasized that the first of these combustion reactions may be lower than 400 °C and the other may be in the range of 400-500 °C. It was observed that there was no mass loss at 1000 °C and the mass was fixed. This is resulted in the RDF1 sample to become residual ash after the temperature exceeded 1000 °C. As a result of the whole combustion, the ash content was 18%, *i.e.* the total mass loss was obtained as 82%.

There is a mass loss in three different regions, and the phase transformations in the DTA curve of the reactions that cause each mass loss are visible in fig. 1(b). In the first zone (0-250 °C), the moisture emitted from the ATY sample and the first mass loss was observed. After this region, two exothermic reaction peaks were observed from the DTA curves, and these peaks were observed as a result of the combustion reactions of the components that came to the ignition temperature and burned. Furthermore, when these combustion reactions occurred, large mass losses were also observed, as shown in the TGA curve. After these serious combustion reactions, that is, after the temperature exceeds 500 °C, it was observed that there is a small mass loss in the values and that there was no mass loss at 1000 °C, thus, that the mass was constant. In the RDF1 sample, this result was residual ash after the temperature exceeded 1000 °C. As a result of the whole combustion, it was found that the ash content was 29%, in other words, the total mass loss was 71%.

Comparison of RDF1 and RDF2 samples showed that the RDF1 sample had less ash amount and more mass loss than RDF2 sample and DTA curves had sharper burning reaction peaks. These results showed that the RDF1 sample would perform better combustion. The DSC analysis were performed to see the DTA curves of the samples more clearly and to determine the combustion temperatures up to 500 °C. The DSC analysis results of the RDF1 sample can be seen in fig. 2.

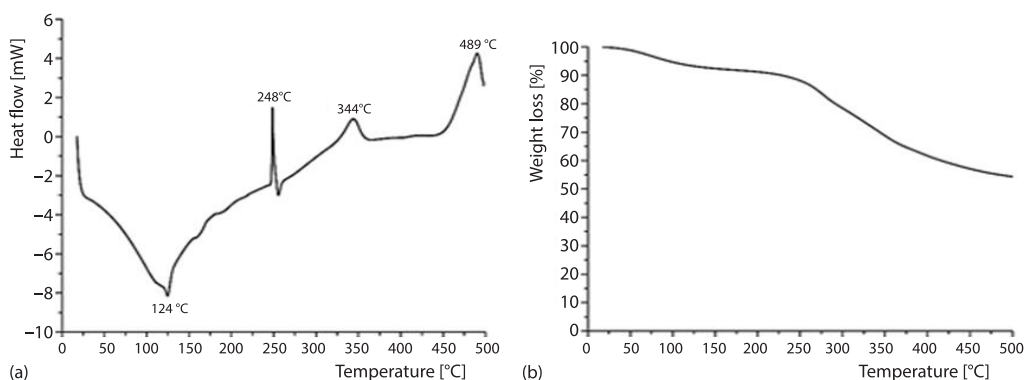


Figure 2. For the RDF1 sample; (a) DSC curve and (b) TGA curve

The figs. 2(a) and 2(b) shows the DSC and TGA curves for the RDF1 sample, respectively. According to the DSC curves, the RDF1 sample first showed an endothermic peak and then three sharp exothermic peaks were found until the temperature reaches 500 °C. The first

peak was a flat endothermic peak in the range of 20-200 °C. Moisture has occurred in this area. After the temperature reached 200 °C, sharp exothermic peaks were observed up to 500 °C. These peaks are the result of combustion reactions. From these results it is clear that a three stage combustion occurred for the RDF1 sample. The first stage took place at 248 °C, which was read as the initial ignition temperature for the RDF1 sample. Subsequently, the second stage took place at 344 °C and the third one was observed at 489 °C. Each reaction in the DSC curves was compensated for a loss of mass in the TGA curves, with DSC and TGA data supporting each other.

Figures 3(a) and 3(b) show the DSC and TGA curves for the RDF2 sample, respectively. According to the DSC curves, the RDF2 sample first showed an endothermic spike peak and then two distinctly exothermic peaks were found up to 500 °C. The first peak was a flat endothermic peak between 20 °C and 200 °C due to moisture output in this region. After the temperature exceeded 200 °C, exothermic peaks up to 500 °C were seen as combustion reactions. It can be said that a two stage combustion occurred for the RDF2 sample. The first step was carried out at 249 °C, which was read as the initial ignition temperature for the RDF2 sample. Subsequently, the second stage took place at 455 °C. Each reaction in the DSC curves was compensated for a loss of mass in the TGA curves, with DSC and TGA data supporting each other. It should be noted that the initial combustion temperatures for the RDF1 and RDF2 samples were almost the same.

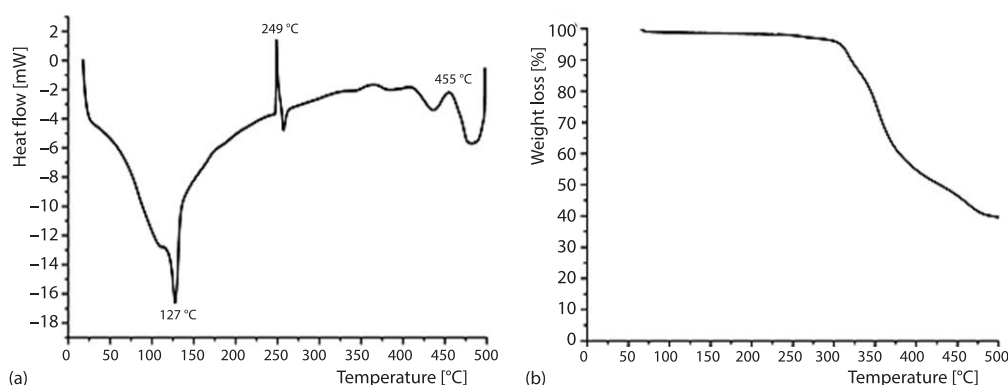


Figure 3. For the RDF2 sample; (a) DSC curve and (b) TGA curve

Conclusions

In this study, RDF1 and RDF2 samples were used and six different analysis were performed: proximate, calorific value, elemental, XRF, TGA, and DSC. The fuel characterization of the samples was examined with these analyses. Some comments were made based on the findings obtained from the measurement.

The calorific value analysis showed that the RDF1 sample had higher heating value between the RDF1 and RDF2 samples. In the data obtained from the proximate analysis results, when a comparison was made between the RDF samples, it was seen that the high volatile content was in the RDF1 sample and therefore, had a low ash content. According to the results of elemental analysis, the RDF1 sample had high C content among RDF samples. This indicates that the RDF1 sample performs better combustion than the RDF2 sample. It was seen that the pollution index for RDF was highest in the RDF1 sample and the amount of chlorine was higher than the RDF2 sample and standards. The high amount of Cl had led us to conclude that PVC

fragments, plastics, paper, and food waste were more present, which led to the formation of Cl in the RDF sample. Due to the high pollution rate, we can say that such important factors of RDF samples need to be improved. To summarize briefly, the content of the matrix components, the remaining ash amount, the calorific value results resulting from the burning of the content and the ash content support each other. The same results were observed as the burning peak in the TGA curves and the accuracy of the analysis results was proven. In the DSC analysis results, the initial ignition temperatures of the samples and whether the other analysis results were supported were checked. The initial ignition temperatures of the samples were almost identical and the combustion temperatures changed over time. Besides, the DSC analysis results supported the other test results, indicating that our samples were made as homogenous as possible and the accuracy of our test results.

The results of the analysis clearly show how different the RDF samples taken from the same region in two different months are different from each other. In addition, the results showed that RDF burned in some months are a fuel whose values such as Cl amount and gas emission can be improved. By doing such studies, the fuel potential of the regions can be examined. The fuels that are improved in this way both increase energy recovery and reduce environmental pollution.

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References

- [1] Shahbaz, M., *et al.*, The Effect of Financial Development on Renewable Energy Demand: The Case of Developing Countries, *Renewable Energy*, 178 (2021), Nov., pp. 1370-1380
- [2] Chen, C., *et al.*, Determinants of Renewable Energy Consumption: Importance of Democratic Institutions, *Renewable Energy*, 179 (2021), Dec., pp. 75-83
- [3] Doytch, N., Narayan, S., Does Transitioning Towards Renewable Energy Accelerate Economic Growth, An Analysis of Sectoral Growth for a Dynamic Panel of Countries, *Energy*, 235 (2021), Nov., 121290
- [4] Unal, F., *et al.*, Energy, Exergy and Exergoeconomic Analysis of Solar-Assisted Vertical Groundsource Heat Pump System for Heating Season, *Journal of Mechanical Science and Technology*, 32 (2018), 8, pp. 3929-3942
- [5] Akdag, A. S., *et al.*, Comparison of Fuel Value and Combustion Characteristics of Two Different RDF Samples, *Waste Management*, 47 (2016), Part B, pp. 217-224
- [6] Bosmans, A., *et al.*, The crucial role of Waste-to-Energy Technologies in Enhanced Landfill Mining: A Technology Review, *Journal of Cleaner Production*, 55 (2013), Sept., p. 10-23
- [7] Consonni, S., *et al.*, Alternative Strategies for Energy Recovery from Municipal Solid Waste – Part A: Mass and Energy Balances, *Waste Management*, 25 (2005), 2, pp. 123-135
- [8] Rotter, V. S., *et al.*, Material Flow Analysis of RDF-Production Processes, *Waste Management*, 24 (2004), 10, pp. 1005-1021
- [9] Caputo, A. C., Pelagagge, P. M., The RDF Production Plants: I Design and Costs, *Applied Thermal Engineering*, 22 (2002), 4, pp. 423-437
- [10] Chang, Y. H., *et al.*, Comparative Evaluation of RDF and MSW Incineration, *Journal of Hazardous Materials*, 58 (1998), 1-3, pp. 33-45
- [11] Wagland, S. T., *et al.*, Comparison of Coal/Solid Recovered Fuel (SRF) with Coal/Refuse Derived Fuel (RDF) in a Fluidised Bed Reactor, *Waste Management*, 31 (2011), 6, pp. 1176-1183
- [12] Robinson, T., *et al.*, Sample Preparation for Thermo-Gravimetric Determination and Thermo-Gravimetric Characterization of Refuse Derived Fuel, *Waste Management*, 48 (2016), Feb., pp. 265-274
- [13] Akdag, A. S., Investigation of Fuel Values and Combustion Characteristics of RDF Samples, M. Sc. thesis, METU Institute of Science and Technology, Ankara, Turkey, 2014
- [14] Hou, S. S., *et al.*, Experimental Study of the Combustion Characteristics of Densified Refuse Derived Fuel (RDF-5) Produced from Oil Sludge, *Fuel*, 116 (2014), Jan., pp. 201-207

- [15] Fellner, J., *et al.*, Determination of the Biogenic and Fossil Organic Matter Content of Refuse-Derived Fuels Based on Elementary Analyses, *Fuel*, 90 (2011), 11, pp. 3164-3171
- [16] Myrin, E. S., *et al.*, The Influence of Food Waste on Dioxin Formation during Incineration of Refuse-Derived Fuels, *Fuel*, 132 (2014), Sept., pp. 165-169
- [17] Ma, W., *et al.*, Chlorine Characterization and Thermal Behavior in MSW and RDF, *Journal of Hazardous Materials*, 178 (2010), 1-3, pp. 489-498
- [18] Marsh, R., *et al.*, Physical and Thermal Properties of Extruded Refuse Derived Fuel, *Fuel Processing Technology*, 88 (2007), 7, pp. 701-706
- [19] Schwarzbock, T., *et al.*, Effects of Sample Preparation on the Accuracy of Biomass Content Determination for Refuse-Derived Fuels, *Fuel Processing Technology*, 153 (2016), Dec., pp. 101-110
- [20] Jamradloedluk, J., Lertsatitthanakorn, C., Properties of Densified-Refuse Derived Fuel Using Glycerin as a Binder, *Procedia Engineering*, 100 (2015), Dec., pp. 505-510
- [21] Porshnov, D., *et al.*, Thermogravimetric Analysis as Express Tool For quality Assessment of Refuse Derived Fuels Used for Pyro-Gasification, *Environmental Technology*, 41 (2019), 1, pp. 29-35
- [22] Porshnov, D., *et al.*, Thermal Decomposition Study of Major Refuse Derived Fuel Components, *Energy Procedia*, 147 (2018), Aug., pp. 48-53
- [23] Nobre, C., *et al.*, Torrefaction and Carbonization of Refuse Derived Fuel: Char Characterization and Evaluation of Gaseous and Liquid Emissions, *Bioresource Technology*, 285 (2019), Apr., 12132
- [24] Yui, K., *et al.*, Measurement and Modelling of Heavy Metal Behaviors during the Incineration of RDF in a Pilot-Scale Kiln Incinerator – Part 1: Modelling Using Multizonal Thermodynamic Equilibrium Calculation, *Pro. Safety and Envir. Protection*, 150 (2021), June, pp. 373-384
- [25] Edo, M., *et al.*, Fate of Metals and Emissions of Organic Pollutants from Torrefaction of Waste Wood, MSW, and RDF, *Waste Management*, 68 (2017), Oct., pp. 646-652
- [26] Zhao, L., *et al.*, Characterization of Singapore RDF Resources and Analysis of Their Heating Value, *Sustainable Environment Research*, 26 (2016), 1, pp. 51-54
- [27] Akdogan, A., Gules, S., Solid Waste Management in Municipalities and an Empirical Research in Provincial Municipalities, *Journal of Contemporary Local Gover.*, 14 (2005), 4, pp. 51-78
- [28] Niessen, W. R., *Combustion and Incineration Processes*, Teylor and Franciz, New York, USA, 2002
- [29] Pronobis, M., Evaluation of the Influence of Biomass Co-Combustion on Boiler Furnace Slagging by Means of Fusibility Correlations, *Biomass and Bioenergy*, 28 (2005), 4, pp. 375-383
- [30] Vamvuka, D., *et al.*, Possibility of Using Paper Sludge in Co-Firing Applications, *Fuel*, 88 (2009), 4, pp. 637-643
- [31] Park, S. W., Jang, C. H., Characteristics of Carbonized Sludge for Cocombustion in Pulverized Coal Power Plants, *Waste Management*, 31 (2011), 3, pp. 523-529
- [32] Resmi, T. C., *Facility and Their Characteristics*, T.R. Official Gazette Wastes to be Accepted to RDF Facility and Their Characteristics, (20140620-8-1 duplicate)
- [33] Manya, J. J., *et al.*, Pyrolysis and Char Reactivity of a Poor-Quality Refuse-Derived Fuel (RDF) from Municipal Solid Waste, *Fuel Processing Tec.*, 140 (2015), Dec., pp. 276-284
- [34] Bialowiec, A., *et al.*, The RDF/SRF Torrefaction: An Effect of Temperature on Characterization of the Product – Carbonized Refuse Derived Fuel, *Waste Management*, 70 (2017), Dec., pp. 91-100
- [35] Kara, M., Environmental and Economic Advantages Associated with the Use of RDF in Cement Kilns, Resources, *Conservation and Recycling*, 68 (2012), Nov., pp. 21-28
- [36] Hwang, I. H., *et al.*, Characterization of Products Obtained from Pyrolysis and Steam Gasification of Wood Waste, RDF and RPF, *Waste Management*, 34 (2014), 2, pp. 402-420
- [37] Reference Document on the Best Available Techniques for Waste Incineration, European Comission Integrated Pollution Prevention and Control, Bruksel, 2006
- [38] Ariyaratne, W., *et al.*, Determination of Fossil Fraction of Refuse Derived Fuel by the Selective Dissolution Method in Calorific Value Basis: Development of Simplified Method, *Fuel*, 98 (2012), Aug., pp. 41-47
- [39] Sarc, R., Lorber, K.,E., Production, Quality and Quality Assurance of Refuse Derived Fuels (RDF), *Waste Management*, 33 (2013), June, pp. 1825-1834
- [40] Tchobanoglous, G., Kreith, F., *Handbook of Solid Waste Management*, McGraw Hill Professional, New York, USA, 2002
- [41] Aracil, I., *et al.*, Semivolatile and Volatile Compounds from the Pyrolysis and Combustion of Polyvinyl Chloride, *Journal of Analytical and Applied Pyrolysis*, 74 (2005), 1, pp. 465-478
- [42] Agrawal, R. K., A Rapid Technique for Characterization and Proximate Analysis of Refuse-Derived Fuels and Its Implications for Thermal Conversion, *Waste Management & Research*, 6 (1998), 3, pp. 271-280

- [43] Cozzani, V., *et al.*, Devolatilization and Pyrolysis of Refuse Derived Fuels: Characterization and Kinetic Modelling by a Thermogravimetric and Calorimetric Approach, *Fuel*, 74 (1995), 6, pp. 903-912
- [44] Skodras, G., *et al.*, A Thermochemical Conversion Study on the Combustion of Residue-Derived, *Fuels*, 9 (2009), Dec., pp. 151-157