Journal of Energy Technology

JET Volume 13 (2020) p.p. 11-28
Issue 4, December 2020
Type of article 1.01
www.fe.um.si/en/jet.html

ANALYSIS OF COMBUSTIBLE FRACTIONS IN MIXED MUNICIPAL WASTE AND PACKAGING AND CALCULATION OF ENERGY VALUE

ANALIZA GORLJIVIH FRAKCIJ V MEŠANIH KOMUNALNIH ODPADKIH IN EMBALAŽI TER IZRAČUN ENERGIJSKE VREDNOSTI

Buble I.[1], Jerina S.[ℜ,2], Seme S.[2], Stergar J.[3,4]

Keywords: mixed municipal waste, mixed municipal packaging, combustible fractions, energy value, solid recovered fuel, TGA analysis

Abstract

The present article analyses combustible fractions in mixed municipal waste and packaging and the calculation of energy value. Methods of thermal treatment of waste and methods of preparation of alternative fuels and classifications are presented and described. The article describes the method of analysis of caloric values with which we determined the energy values of individual fractions. For the research, we also used two thermal analyses, with which we considered individual fractions, thermogravimetric analysis, and differential dynamic calorimetry. The article presents the results of both thermal analyses, with which we observe the responses of individual types of plastics at different

ℜ Corresponding author: Simon Jerina, University of Maribor, Faculty of Energy Technology, Hočevarjev trg 1, Krško, Tel.: +386 40 453 805, E-mail address: simon.jerina@gmail.com

[1]Kostak d.d., Leskovška cesta 2a, Krško

[2]University of Maribor, Faculty of Energy Technology, Hočevarjev trg 1, Krško

[3]University of Maribor, Faculty of Chemistry and Chemical Technology, Smetanova ulica 17, Maribor, Slovenia

[4]University of Maribor, Faculty of Medicine, Taborska ulica 8, 2000, Slovenia

temperatures and the change in physical and chemical properties. The problem we have analysed in this article is mainly recyclable plastic that can no longer be reused due to various factors. The results of the structural analysis of household waste collection are also presented and described; on the basis of the analysis, the energy value of the container of mixed municipal waste and the reasonableness of waste reuse are recalculated.

Povzetek

Članek obravnava analizo gorljivih frakcij v mešanih komunalnih odpadkih in embalaži ter preračun energijske vrednosti. Predstavljeni in opisani so načini termične obdelave odpadkov ter metode priprave alternativnih goriv in klasifikacija. V članku je opisana metoda analize kaloričnih vrednosti, s katero smo določali energijsko vrednost posameznih frakcij. Za namen raziskave smo uporabili tudi dve termični analizi, s katerimi smo obravnavali posamezne frakcije, termogravimetrično analizo in diferenčno dinamično kalorimetrijo. V članku so predstavljeni rezultati obeh termičnih analiz, s katerimi opazujemo odzive posameznih vrst plastike pri različnih temperaturah ter spremembo fizikalnih in kemijskih lastnosti. Problematiko, ki smo jo analizirali v tem članku, predstavlja predvsem plastika, ki se lahko reciklira, vendar je zaradi različnih dejavnikov ni mogoče več ponovno uporabiti. Predstavljeni in opisani so tudi rezultati strukturne analize zbiranja odpadkov v gospodinjstvih in na podlagi analize preračuna energijska vrednost zabojnika mešanih komunalnih odpadkov ter smiselnost ponovne uporabe odpadkov.

1 INTRODUCTION

Waste overcrowding is a major issue today. Ways to prevent the accumulation of waste material effectively are being sought. Utility companies collect waste in their collection centres. Waste material is classified according to its usability (and non-usability). At the same time, great emphasis is placed on the field of recycling. For the most part, the public is insufficiently aware of waste separation and the method of proper separation. There are several types of waste separation and collection. Collection begins with an ordinary household, for which purpose mixed municipal waste and mixed packaging. In some cases, bio-waste is separated in the first phase. With the right approach to waste management, we can contribute significantly to reducing the accumulation of waste and waste materials. Through detailed analyses and studies, waste can be separated to such an extent that it is reused, and disposed of as little as possible. Waste is also strictly defined according to legislation, and the consequent management of all types of waste differs at local, regional, and national levels. These classifications help in planning and defining methods of waste separation and collection. The reuse or recycling of waste requires precise information on the source and composition, the means and strategy of management can be determined. The definition of waste, of course, facilitates its classification into different groups, but such classification extremely demanding due to the diversity of waste, but only in this manner can it be handled consistently. Due to the heterogeneity of the waste material, we must strive for further homogenization.

1.1 Waste issues in Slovenia

In Slovenia, the amount of waste is increasing every year; about 8 million tons of waste are generated annually. The largest share is accounted for by construction waste, specifically, 59%; waste from thermal processes represents about 13%, waste from metal and wood processing accounts for 7%, and waste is also generated in waste management facilities themselves (about 4%). Other types represent 5% of all generated waste. Municipal waste represents approximately one million tons, which is 12.5% of all waste and means that the population of Slovenia generates an average of 495 kilograms per person of waste per year. In the past, most waste was disposed of in dedicated landfills. With municipal waste management centres, the trend of waste disposal is significantly reduced as the recycling rate has increased. In Slovenia, about 59% of all municipal waste is recycled, *[1].*

1.2 Types of waste that can be used for alternative fuels

Annex 7 of the Waste Management Regulation (1358), page 3194, *[2]*, describes the division of waste into individual types. The waste classification list is divided into 20 groups, as can be seen in Table 1. The source of the waste must be identified for classification.

Table 1: *Waste classification [2]*

1	Wastes from prospecting, mining, quarrying, physical and chemical processing of mineral resources
2	Wastes from agriculture, horticulture, aquaculture, forestry, hunting and fishing, food preparation and processing
3	Wastes from wood treatment and processing and production of particleboard and furniture, fibre, paper, and board
4	Wastes from the leather, fur, and textile industries
5	Wastes from oil refineries, natural gas refining, and coal pyrolysis
6	Wastes from inorganic chemical processes
7	Wastes from organic chemical processes
8	Wastes from manufacture, formulation, supply and use of surface preservatives (paints, varnishes and enamels), adhesives, sealants, and printing inks
9	Wastes from the photographic industry
10	Wastes from thermal processes
11	Wastes from chemical treatment and surface protection of metals and other materials; hydrometallurgy of non-ferrous metals
12	Wastes from shaping processes and physical and mechanical surface treatment of metals and plastics

13	Oil wastes and wastes from liquid fuels (excluding edible oils referred to in points 05 and 12)
14	Waste organic solvents, refrigerants and propellants (excluding 07 and 08)
15	Packaging waste; absorbents, cleaning cloths, filter media and protective clothing not elsewhere specified or included
16	Wastes not otherwise specified in the classification list
17	Construction and demolition wastes (including excavations from contaminated sites)
18	Wastes from health or veterinary medicine and/or related research (excluding wastes from kitchens and restaurants not directly derived from health or veterinary medicine)
19	Wastes from waste treatment facilities, treatment plants and from the preparation of drinking water and water for industrial use
20	Municipal waste (household and similar wastes from trade, industry and the public sector), including separately collected fractions

Wastes that can be used in processing for alternative fuels are in groups:

- 04 01 09 wastes from finishing and finishing of fur and leather,
- 07 02 13 Waste plastics,
- 15 01 01 Paper and paperboard packaging,
- 15 01 02 Plastic packaging,
- 15 01 06 Mixed packaging,
- 17 09 04 Mixed construction and demolition wastes other than those mentioned in 17 09 01, 17 09 02, and 17 09 03,
- 19 12 12 Other wastes (including mixtures of materials) from mechanical treatment of waste other than those mentioned in 19 12 11
- 20 01 01 Paper and paperboard
- 20 01 39 Plastic,
- 20 03 01 Mixed municipal waste,
- 20 03 07 Bulky waste, *[3].*

Products of alternative fuel production are most often classified as:

- 19 12 10 Combustible waste (fuel derived from waste),
- 19 12 12 Other wastes (including mixtures of materials) from mechanical treatment of wastes other than those mentioned in 19 12 11, *[3].*

2 WASTE MANAGEMENT AND TREATMENT

The preparation of an alternative fuel requires a multi-stage treatment to achieve the desired quality. High-calorie fuel is used in primary kilns or cement plants. The preparation of this fuel takes place in the process of sorting waste material. To achieve the efficiency of the sorting process, it is necessary to reduce the dimensions of the material and then separate it into 2D and 3D material. 3D material often contains several impurities in the form of heavy metals and larger pieces of building material. Also, 3D material is more demanding for mechanical processing. In the first step, magnetic separation, it is necessary to eliminate materials containing iron (Fe). This is followed by Eddy current separation to remove non-ferrous metals. Prior to the grinding process, air separation in an air separator is required to maintain the quality of the solid fuel, as all remaining heavy fraction is eliminated in this process. The particle size of the solid fuel is determined by the acquirer. Materials are usually ground to a size >30 mm. A similar separation procedure is used for 2D materials, *[4].*

2.1 Heat treatment of waste

Incineration or co-incineration is used for different types of waste. Heat treatment is only part of the complex waste treatment technology used to generate energy or reduce waste. From the chemical point of view, the waste incineration process can be divided into three phases.

In phase one, drying and degassing takes place. This phase does not require oxygen, as it depends only on the supplied heat, *[5].* Evaporation starts in the first phase, mainly of hydrocarbons and water; it occurs between 100 °C and 300 °C. The second phase is the pyrolysis and gasification of alternative fuels or waste. Pyrolysis represents further decomposition without the presence of oxygen at a temperature between 250 °C and 700 °C. Gasification of carbon residues with water vapour and CO in residues occurs at temperatures between 500 °C and 1000 °C. In the third stage, the flammable gases formed in the first and second stages are oxidized and burned at a temperature between 800 °C and 1450 °C. This phase is called oxidation, *[5].*

2.2 Heat treatment technologies

Different types of waste also require the use of different types of heat treatment. The most common heat treatment technologies are:

- grate incinerators,
- rotary kilns,
- fluidized beds,
- pyrolysis and gasification systems.

3 ALTERNATIVE FUELS FROM WASTE

Alternative fuels and the qualification system can be defined in several ways. In addition to the values and restrictions set by the legislation for the different uses of solid fuels from waste, in practice, the composition and properties of the fuel are determined by the supplier and the user. The most important parameters for fuel are fraction size, net calorific value, sulphur, fluorine, ash content, moisture, organic carbon content as well as material density and heavy metal content in the fuel, *[6].*

Regardless of its use and method, alternative fuel from waste must meet several criteria:

- caloric values,
- low chlorine content,
- quality control,
- particle size,
- density,
- a sufficient amount of fuel with the required properties, *[6].*

3.1 Solid Recovered Fuel

Solid Recovered Fuel (SRF) is a solid fuel from waste with calorific values ranging from 11 to 25 MJ/kg. Typically, fuel is produced from high-calorie sorted mixed municipal waste and industrial waste. The size of individual fuel particles is between 5 and 300 mm, *[4].*

Table 2: *Classification of solid alternative fuels, [7]*

PARAMETERS	SHARE	UNITS	1. Class	2. Class	3. Class	4. Class	5. Class
Net calorific value	arithmetic mean	MJ/kg	≥ 25	≥ 20	≥ 15	≥ 10	≥ 3
Chlorine (Cl)	arithmetic mean	% (m/m)	≤ 0.2	≤ 0.6	≤ 1.0	≤ 1.5	≤ 3.0
Mercury (Hg)	median	mg/MJ	≤ 0.02	≤ 0.03	≤ 0.08	≤ 0.15	≤ 0.5
Mercury (Hg)	80th percentile value	mg/MJ	≤ 0.04	≤ 0.06	≤ 0.16	≤ 0.30	≤ 1.0
Cadmium (Cd)	arithmetic mean	mg/kg	≤ 1.0	≤ 4.0	≤ 5.0	≤ 5.0	≤ 5.0
Sulphur (S)	arithmetic mean	% (m/m)	≤ 0.2	≤ 0.3	≤ 0.5	≤ 0.5	≤ 0.5

There are several types of solid SRF fuel classification. They can be divided by quality (Table 3) or by using heat treatment technology (Table 4). Of course, each classification needs verified fuel quality parameters and properties.

Table 3: *Classification of different SRF-qualities, [4]*

Parameters	**SRF – specifications**						
	Coal-fired power station	**Calciner**	**Grate firing**	**Fluidized bed**	**HOT DISC cement kiln (HDF)**	**Primary burner cement kiln (PBF)**	**Blast furnace (steel plant)**
			Utility boilers				
Net calorific value MJ/kg]	11–15	11–18	11–16	11–16	14–16	20–25	< 25
Particle size [mm]	< 50	< 50–80	< 300	<20– 100	< 120	< 10–30	< 10
Oversize [%]	0	< 1	< 3	< 2	*	< 1	0
Impurities (extraneous material) [w %]	< 1	0	< 3	< 1–2	*	< 1	0
Chlorine (Cl) [w %]	< 1.5	< 0.8	< 1.0–0.8	< 1.0–0.8	0.8–0.6	< 1.0–0.8	< 2
Ash [w %]	< 35	*	*	< 20	20–30	< 10	< 10

4 POLYMERS IN WASTE AND THEIR PROPERTIES

There are many types of polymers. In waste, they are divided into seven subgroups. Some types of plastic can be recycled, while others are non-recyclable. The problem described in this article is mainly plastic that can be recycled, but due to various factors (incorrect separation, incorrect storage and use), it can no longer be recycled. Such waste in many cases ends in landfills. To reduce the disposal of non-degradable and non-reusable plastics, heat treatment is therefore essential. The largest share is represented by plastic in waste, which is used as an alternative fuel, and it also represents the raw material that in most cases has the highest net calorific value and thus increases the value of the fuel itself.

Plastic is an extremely important component. Many substances are being investigated to replace it with other raw materials, but in the short term life without it will certainly not be possible. Therefore it is extremely important that it is used for other purposes, such as obtaining energy by heat treatment. Plastics are divided according to SPI labels, and these labels help individual and waste processors to classify plastics into groups for further sorting and processing. Data on different types of plastics are presented in Table 4.

Table 4: *Classification of plastics in waste by groups*

TYPE OF PLASTIC	SPI LABEL	USAGE
Polyethylene terephthalate (PET or PETE)	1 PETE	Drink bottles
High-density polyethylene (HDPE)	2 HDPE	Packaging for milk, cosmetics
Polyvinyl chloride (PVC)	3 PVC	Plastic wrappers, various toys, spray bottles
Low-density polyethylene (LDPE)	4 LDPE	Shopping bags, plastic covers, reusable plastic
Polypropylene (PP)	5 PP	Food packaging
Polystyrene (PS)	6 PS	Plastic cutlery, various food packaging
Other	7 OTHER	Other packaging that cannot be classified in any of the above groups

Polyethylene terephthalate (PET or PETE) or polymer PET is a type of polyester and represents one of the most important groups of packaging material, as it is widely used for packaging beverages. PET is primarily useful because of its properties. It has low density, good light transmission, resistance to elevated temperatures, good chemical resistance and dimensional stability and high toughness, *[8].* High-Density Polyethylene (HDPE) and Low-Density Polyethylene (LDPE) are the simplest polymers, at least in terms of chemical structure, which ranks them among the most represented synthetic polymers also in terms of production. They generally have high toughness, are flexible and chemically resistant, but have lower thermal stability and strength. Low and high-density polyethylenes have a characteristic low melting point. They are distinguished by density, namely HDPE ρ= 0.940–0.965 g/cm³, and LDPE density ρ = 0.915–0.940 g/cm³, *[8].* Polyvinyl chloride or PVC can be soft or hard. In connection with its properties, PVC has a high resistance to organic chemicals, and lower to heat, light and mechanical influences. PVC is an environmental problem mainly due to the content of phthalate-based plasticizers. An additional problem is the unreacted monomer in the form of vinyl chloride, which is considered to be carcinogenic, *[8].* Polypropylene (PP) is one of the lightest synthetic polymers with a density of ρ= 0.90–0.91 g/cm³. It is similar in basic properties to LDPE but has higher strength, high gloss, and a higher melting point. It is resistant to water and most organic solvents. The problem is oxidation and decomposition at elevated temperatures, *[8].* Polystyrene (PS), compared to other polymers, is slightly harder and stiffer, as well as more brittle. It is unsuitable for use at higher temperatures. It is highly susceptible to photochemical degradation in light, *[8].*

5 RESULTS

5.1 Structural analysis of mixed municipal solid waste and mixed packaging

Mixed municipal solid waste (MSW) was classified into individual fractions: plastics, paper and cardboard, textiles and footwear, wood waste, rubber, glass, metals, construction waste, electronic devices, kitchen waste, including food scraps and other discarded waste, biological waste (mostly waste landscaping) and some other waste that we could not separate. Table 5 shows the percentage of waste.

Table 5: *Quantity of individual fractions in the analysed container in MSW*

FRACTION	Quantity %
Plastic	16.5
Paper and cardboard	20.5
Textiles and footwear	3
Wood waste	4
Rubber	4.5
Glass	6
Metals	5.5
Construction waste	7,5
Electronic devices	5
Kitchen waste (food scraps and other)	17.5
Biological waste	7
Other	3
SUM	100

As part of the research, we also analysed the percentage of individual fractions in MP, using a 30 kg sample. From Table 6, we determine which fractions were in the container. Tetra packs of various packaged liquids appeared in the container to the greatest extent (31%), followed by bottles (25%), aluminium cans (22%). The fractions that remained were paper and cardboard (12%) and glass (3%). Some waste was also of biological and other origins, which belongs more to MSW (7%). We found that 43% of this packaging waste is recyclable, which means that no additional treatment is required. As much as 57% was dirty packaging that was not suitable for recycling and needed to be further processed for alternative fuels or reuse.

Table 6: *Structural analysis of MP*

FRACTION	Quantity [%]	Suitable for recycling [%]	Processing required [%]
Bottles	25	15	10
Cans	22	22	0
Tetrapack	31	2	29
Paper and cardboard	12	3	9
Glass	3	1	2
Other (MSW)	7	0	7
SUM	100	43	57

In Table 7, the MP structure was further elaborated, according to the needs of analysis in the research. Plastics were divided into seven basic groups, as presented in Table 4. We see that most packaging waste has a PET composition (47%), followed by HDPE and LDPE with 16 and 17%. Other polymers are approximately evenly represented.

Table 7: *Polymers in MP*

Type of plastic in MP	Quantity [%]
Polyethylene terephthalate (PET or PETE)	47
High density polyethylene (HDPE)	16
Polyvinyl chloride (PVC)	3
Low density polyethylene (LDPE)	17
Polypropylene (PP)	5
Polystyrene (PS)	4
Other	8
SUM	100

5.2 Samples

As part of the research, we analysed 50 samples of SRF fuel: 25 samples of fuel of lower quality and 25 samples of higher quality fuel. Gross and net calorific value and moisture content were analysed in the samples. We also performed a calorimetric analysis for the two individual most represented fractions in the structural analysis, plastic foil and cardboard. Thermogravimetric analysis and differential dynamic calorimetry were also performed for four plastic samples. In total, we analysed approximately 80 kg of waste.

5.3 Results of calorimetric analysis

For the analysis of the calorific value of waste, we used 25 samples of SRF fuel of lower quality and 25 samples of SRF fuel of higher quality. We also analysed the calorific value of the foil and cardboard in Figure 1.

Figure 1: *Photos of foil (up) and cardboard (down)*

Figure 2 (below) shows the results of the calorimetric analysis of SRF fuel of lower quality. The graph presents the results of caloric values as a function of moisture. The samples had different moisture content; it is evident that those samples that contained more moisture have a slightly lower calorific value. Values range between 12 MJ/kg and 24 MJ/kg. According to the obtained results, the fuel can be classified into the classes given in Table 4 (Classification of solid fuels). Eight samples are thus classified into the fourth quality class, sixteen samples into the third quality class, and one sample exceeds the value of 20 MJ/kg and could be classified in the second quality class. Similarly, we analysed the calorific values of SRF fuel samples of higher quality. Figure 2 clearly shows how the moisture content reduces the calorific value of the fuel. The net calorific value of the samples ranged from 10 MJ/kg to 33 MJ/kg. These samples were also divided into quality classes. In the fourth class, we add one sample, in the third three, the second class comprises eleven, and the first ten samples.

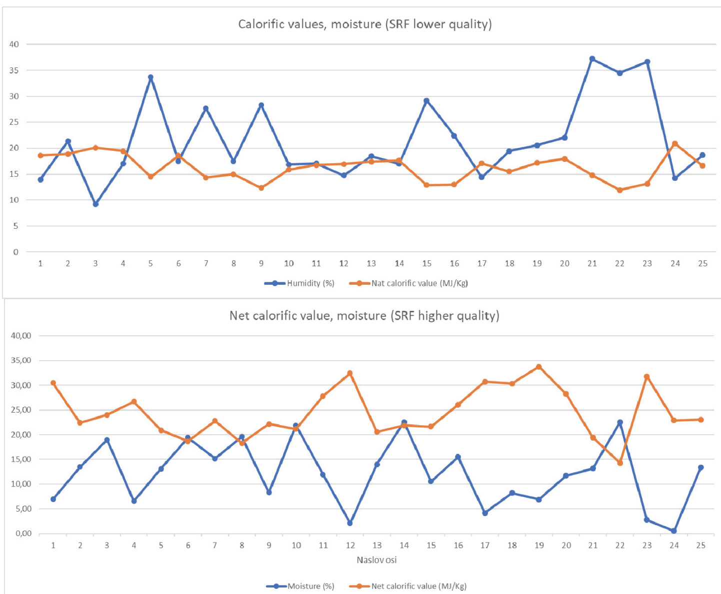


Figure 2: *Calorific values compared to the moisture content of individual fuel samples of lower quality (up) and higher quality (down)*

5.4 Results of thermogravimetric analysis and differential dynamic calorimetry

To facilitate the understanding of the behaviour of solid alternative fuels in heat treatment, we performed a laboratory analysis of the fractions that contribute the highest value of caloric energy to the fuel, namely plastics. We analysed four samples. The results of the analysis were compared with the research already conducted in this field. In the case of samples 1, 2 and 3, the measurement was carried out in the temperature range from 30 to 1000 °C with a temperature step of 20 K/min, in an inert nitrogen atmosphere, with a gas flow of 100 mL/min. In the case of sample four, the measurement was made in the range from 30 to 700 °C with a temperature step of 10 K/min, in an inert nitrogen atmosphere, with a gas flow of 100 mL/min.

Plastic polymers in waste are composed of synthetic or natural materials, chemical building blocks of monomers are placed in high molecular weight chains, and the main element is carbon. Other elements are oxygen, hydrogen, nitrogen and other inorganic and organic elements. Research has shown that the thermal decomposition of plastics takes place at elevated temperatures. In a study of the thermal analysis of alternative fuel components, *[9]*, it was found that plastics behave differently at elevated temperatures.

Sample 1, plastic bottle belongs to the group of PET or PETE plastics. Figure 3 (left) shows that the sample decomposes almost completely. Weight drops by 84.3% or 8.45 g. The initial or initial weight of the sample was 10.0260 mg. The sample began to decompose at a temperature of 434.20 °C and completely decomposed to a temperature of 497.94 °C, which is consistent with the results from *[9]*. The decomposition temperature, at which the mass drop is 50%, is 468.91 °C, determined by means of the 1st lead function (DTG-curve = differential thermogravimetry, differential thermal gravimetry – 1st lead of the thermogravimetric curve over time). Figure 3 (left) shows only one jump, which indicates that the decay takes place in one step, as also found in *[9].* Figure 3 (right) shows the energy changes of sample 1, which has a starting weight of the sample was 6.34 mg. For substances that are partially crystalline, the melting point and the glass transition temperature can be determined. In our case, we see that the glass transition temperature is 81.99 °C and the melting point is 250 °C, with the enthalpy of melting, being released during the melting process, 271.68 mJ or 42.25 J/g.

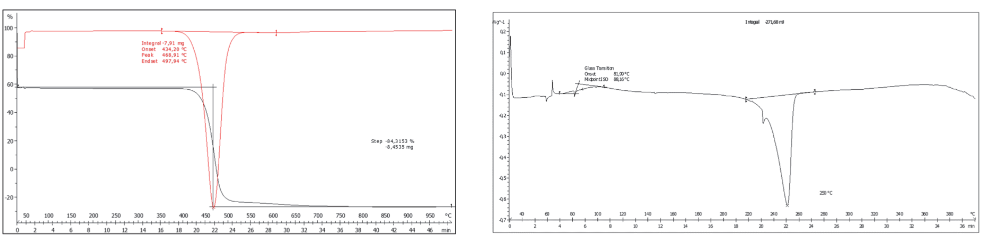


***Figure 3**: TGA analysis of sample 1 (left), DSC analysis (right)*

Sample 2, yogurt packaging, belongs to the PS plastic group. Figure 4 shows that the initial weight of the sample was 8.101 mg; the sample disintegrated almost completely, and the mass decreased by 7.8204 mg, representing 96.54%. The decomposition process started at a temperature of 359.85 °C and lasted until a temperature of 554.61 °C. Compared to the TGA analysis in *[9]*, depending on the composition of the crucible belonging to the PS group, the temperature change occurred earlier. We realized that for more accurate measurements, the exact chemical composition of individual plastics should also be determined, as these are very different from each other. The decomposition temperature, at which the mass has fallen by 50%, is 452.14 °C, determined by means of a DTG curve.

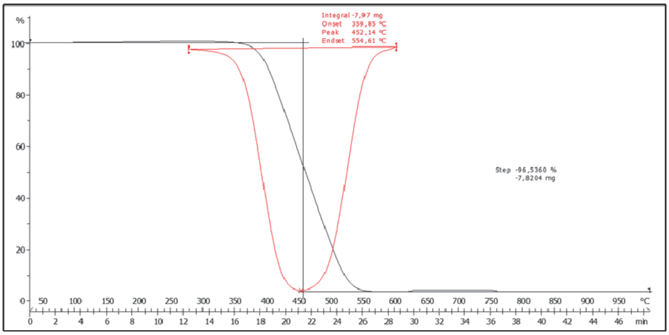


Figure 4: *TGA analysis of sample 2*

Sample 3, foil packaging, belongs to the group of PP plastics. Figure 5 (left) shows that the initial weight of the sample was 6.5010 mg; the sample completely disintegrated and the mass decreased by 99.39% and 6.46 mg, respectively. The sample decomposed in the temperature range from 437.06 °C to 534.36 °C. The DTG curve showed a 50 % drop in mass at 486.90 °C. Compared to the analysis [9], we can see that the degradation occurred at a higher temperature, which means that our sample is more resistant to temperature changes. Figure 5 (right) shows that the sample melted and that the melting point was 169 °C, which is much lower than in the case of sample 1. 410.39 mJ of energy was released in the melting process.

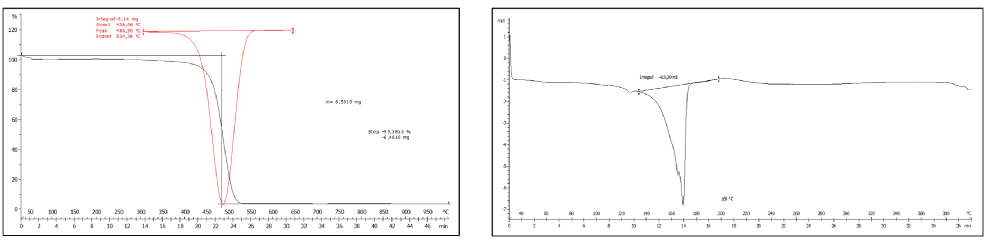
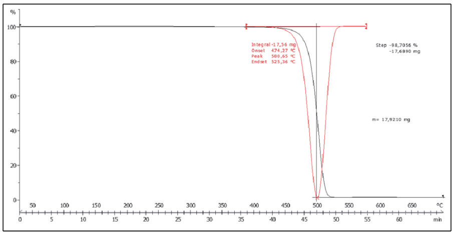


Figure 5: *TGA analysis of sample 3 (left), DSC analysis (right)*

Sample 4, shampoo packaging, belongs to the group of HDPE plastics. Figure 6 (left) shows that this sample also completely disintegrated. The initial weight of the sample was 17.8210 mg, and the final weight was 17.6890 mg, representing a 98.7 1% decrease. The sample began to decompose at 474.27 °C and completely decomposed at 525.36 °C. Compared to the study in *[9]*, the temperature range also differs slightly in this sample, but only by a few degrees; we can conclude that the results of the analysis are very similar. Figure 6 (right) shows that the initial weight of the sample was 11.7 mg, that this sample also melted and that the melting point was 133 °C, which is slightly lower than in the case of the Jamnica bottle and the flaxseed packaging. During the melting process, 1945.54 mJ of energy or 166.29 J/g was released.



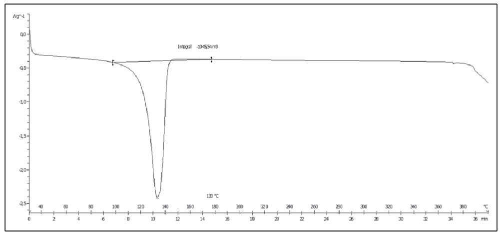


Figure 6: *TGA analysis of sample 4 (left), DSC analysis (right)*

If we compare the samples, we see that they differ slightly from each other in terms of temperature resistance. For sample 1 (PET), decomposition begins at 434.20 °C, the first temperature change of sample 2 (PS) is at 359.85 °C; for sample 3 (PP) the temperature change occurs at 437.06 °C, and sample 4 (HDPE) is the most heat-resistant - the change starts at 474.27 °C. It is true that all samples decompose within a given temperature range. Based on the results of the analysis, we can determine the order of durability of the considered plastics, from the least to the most durable: PS <PET <PP <HDPE. We found that our results were the same as in the comparative analysis *[9]*, in which they determined the same order of temperature resistance.

5.5 Calculation of energy value of containers

With the help of all the collected results, we also calculated the energy values of the container. After structural analysis, we determined the calorific values of individual fractions found in the literature and the calorific values obtained in the calorimetric analysis. For the calculation, we used the average values of the collected calorific values for the mass of 1 ton of alternative fuel.

The energy value was calculated using equation (5.1):

$$E_{odp} = \frac{NKV \times m}{3,6} \tag{5.1}$$

where:

- NKV – Net calorific value
- m – mass of fuel

The results of the calculation are presented in Table 8.

Table 8: *Calculation of energy value in samples used in research*

Analysed fuels	Calorific value [MJ/kg]	Mass [kg]	Calculation of energy value [kWh]
SRF of lower quality	16.29	1000	4.5
SRF of higher quality	24.50	1000	6.8
MP container	18.46	1000	5.1

According to the obtained average calorific values, the treated fuel of higher quality has the highest calorific value. The fractions analysed in the container's structural analysis also have a satisfactory calorific value and would probably represent a much larger share of the energy value after additional processing and potential enrichment with more caloric fractions.

6 CONCLUSION

Based on the results of structural analyses, we performed calorimetric analysis on fifty samples of SRF fuel and two samples of individual fractions that were most represented. The results were defined using classification tables and divided into quality classes. Due to the great influence of plastic, we performed thermal analysis. The results showed that the samples differed slightly in temperature resistance. It is true, however, that all samples decayed within a given temperature range. Based on the results of the analysis, we can determine the order of durability of the analysed plastics, from the least to the most durable: PS <PET <PP <HDPE. We found that our results are comparable to the results from the literature, and we can conclude that the performance of the experiments was of high quality. With the help of all the previously mentioned methods, we conclusively determined the energy value of our samples. The fractions analysed in the structural analysis of the container had a satisfactory calorific value compared to the treated SRF fuel. However, after additional processing and potential enrichment with more caloric fractions, they would probably represent a much higher share of energy value. Summarizing the entire research, we realised that waste represents both energy and user value. Better public awareness could make it easier to present the purposes of waste heat treatment and reuse.

7 Acknowledgements

We would like to thank Kostak d.d. for enabling calorimetric analysis of samples in the laboratory of the company's Waste Management Center. Thanks are also due to the Faculty of Chemistry and Chemical Engineering, University of Maribor, where we performed two thermal analyses of the samples, thermogravimetric analysis (TGA) and dynamic differential calorimetry (DSC).

References

[1] Avaliable: https://www.stat.si/StatWeb/News/Index/8419 (5. 7. 2020)

[2] **Waste Management Regulation**. Uradni list RS, 2008, nr. 34/08 in 103/11.

[3] **R. Sarc, K. E. Lorber, R. Pomberger, M. Rogetzer, and E. M. Sipple**: *Design, quality, and quality assurance of solid recovered fuels for the substitution of fossil feedstock in the cement industry*, Waste Management & Research, Vol. 32(7), p.p. 565–585, 2014.

[4] **K. E. Lorber, R. Sarc, A. Aldrian**: *Design and quality assurance for solid recovered fuel* Waste Management & Research, Vol. 30(4), p.p. 370–380, 2012.

[5] **F. Neuwahl, G. Cusano, J. G. Benavides, S. Holbrook, S. Roudier:** *Best Available Techniques (BAT) Reference Document for Waste Incineration*, 2019.

[6] **R. Sarc, K. E. Lorber:** *Production, quality and quality assurance of Refuse Derived Fuels (RDFs)*, Waste Management, Vol. 3, p.p. 1825–1834, 2013.

[7] **Regulation on the processing of non-hazardous waste into solid fuel and its use**. Uradni list RS, 2014, nr. 96/14.

[8] **R. Gregor**: *Embalaža in varstvo okolja: zahteve, trendi in podjetniške priložnosti*, Maribor, Založba Pivec, 2008.

[9] **D. Porshnov, V. Ozols, L. Ansone-Bertina, J. Burlakovs, & M. Klavins:** *Thermal decomposition study of major refuse derived fuel components*, Energy Procedia, 147, 48–53, 2018.

Nomenclature

(Symbols)	(Symbol meaning)
MSW	Municipal Solid Waste
MP	Mixed Packaging
SRF	Solid Recovered Fuel
MJ	Megajoule
kWh	Kilowatt hour
Kg	Kilogram
PET or PETE	Polyethylene terephthalate
HDPE	High density polyethylene
LDPE	Low density polyethylene
PVC	Polyvinyl chloride
PP	Polypropylene
PS	Polystyrene
TGA	Thermogravimetric analysis
DSC	Dynamic differential calorimetry
SPI	Resin Identification Code
MJ/kg	Megajoule/kilogram
mm	Milimeter
w%	Ash content
°C	Degree Celsius
Fe	Iron
CO	Carbon monoxide

g/cm³	Gram/cubic centimeter
ρ	density
Eodp	Energy of waste
NKV	Net calorific value