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Fixed-Bed Gasification and Pyrolysis of Organic Fraction of MSW Blended with Coal Samples

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Buildup of vast quantities of municipal solid waste (MSW) including refuse derived fuel, organic fraction around the urban areas has negative environmental consequences. Gasification and pyrolysis of municipal solid waste could be an attractive option to utilize or convert to a valuable product. This study investigates the thermochemical properties of refuse derived fuel (RDF), organic fraction of MSW (Org MSW) and coal samples. Along with proximate and elemental analysis, calorific values were provided for RDF, MSW organic fraction, and coal samples. This followed by the thermogravimetric analysis of the same samples. In addition, Org MSW MSW and coal samples were blended in a proportion of 0.5/0.5 and 0.25/0.75 and then thermally treated in horizontal tube furnace both under air and inert gases to investigate the pyrolysis and gasification processes. TGA tests revealed that volatile content from Org MSW and RDF begin to be emitted at temperatures above 180-200 °C. Org MSW and RDF lose all their volatile contents at 500 °C and 700 °C. Pyrolysis experiments revealed that below 500 °C mostly tars are formed from Org MSW. Organic MSW and coal 0.5/0.5 blends yielded higher methane concentrations than coal or MSW alone, reaching 35-37 % at 800 °C. It could be concluded that both fixed bed and thermogravimetric method analysis have provided a good result to investigate the gasification and pyrolysis processes.

1. Introduction

Public and industrial sectors in Kazakhstan rely on low rank and cheap coal resources (IEA CCC, 2011). As a result, a long-term discussion on the penetration of renewable energy technologies such as solar, wind and biomass taken place into the energy sector of the country. The difficulties of implementing renewable energy sources were also associated climate condition of the country (IEA CCC, 2011).

In spite of recent improvements in the field of waste management, the sector of waste management in Kazakhstan is still in its infancy and has low public attention. Waste collection and utilization can be considered insufficient enough. Sanitary landfilling remains the most affordable option and, in most cities, it is treated without separation of recyclables (Inglezakis et al., 2017). Typically, just one-quarter of rural population is covered with waste collection system. In cities, up to 97 % of MSW are taken to uncontrolled or bellow standard sanitary landfills. The only authorized landfill that was designed according to environmental standards is located in Astana city. Two MBT plants are operating in two largest cities of Kazakhstan, one in Astana and one in Almaty. Currently, no waste-to-energy plants exist in Kazakhstan (Inglezakis et al., 2018).

Generally, after separation of recyclables (paper, plastics, metals, glass, wood, textiles and leather, and electronics) the remaining material can further be classified into three material streams such as: non-recyclable high calorific value combustibles, low calorific value material and inerts. Typically, non-recyclable combustible stream consists of degraded plastics (LDPE, HDPE, other plastics), degraded paper, wood, textile and leather, which further can be processed for production of refuse derived fuels (RDF). Low calorific value stream mainly

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consists of materials with high moisture content, such as food waste, gardening waste and some amount of paper and plastics left after separation of high calorific value stream.
Inglezakis et al., conducted a pre-feasibility study for waste-to-energy plant in Astana (Inglezakis et al., 2015). This study compared two options as landfill biogas-based power plant and waste incineration with cogeneration plant. Authors also pointed to the lack of information on basic thermal characteristics for MSW or its streams in Astana. Due to the lack of information, authors had to use data available from the literature (Inglezakis, et al., 2015). Typically, MSW fuel properties widely vary due to differences in their morphological composition which affects proximate and ultimate content of fuel, moisture content, and calorific values. Present study eliminates these gaps as well by providing characterization of Organic fraction of MSW.
Concurrent technologies for incineration and landfill biogas are gasification and pyrolysis (Liu et al., 2015). Both technologies originally were developed for fossil fuels, but later were adopted for MSW thermal treatment too. In practice, any carbonaceous solid fuel combustion or thermal decomposition processes go in a number of stages. First stage is drying process of fuel particles. The second stage is devolatilization, which also can be called as pyrolysis if the process is limited to this stage. During this stage fuel particles release volatiles which transform into non-condensable materials containing pyrolysis gases, condensable stream with long chain hydrocarbons (tars, oils and naphtha), and oxygenated compounds (phenols and acids). The solid residual in the form of char, consists mainly fixed carbon and ash. During the third gasification stage, gaseous and solid products undergo further combustion reactions. At this stage, pyrolysis products mentioned above react with oxygen and all solid and condensable materials convert into the gas phase. The gasification products mainly contain CO, H_2, CH_4, CO_2, and H_2O. Combustion stage occurs when all pyrolysis and gasification products are fully oxidized (Liu et al, 2015). Gasification process is typically maintained at air-to-fuel stoichiometric ratio between 0.3-0.4 (ER) (Collot et al., 1999). Manipulating temperature, heating rate, pressure, supply of oxygen and steam, process can be optimized for production of a produced gas with a desired quality.
Pyrolysis is a thermal cracking process in an inert atmosphere and in the absence of an oxygen (Hwang et al., 2014). Pyrolysis produces three streams of materials: gas, liquid, and solid. Process temperature is typically between 400 °C and 800 °C. Typically, slow pyrolysis occurs in fixed/moving bed reactors and in rotary kiln reactors with slow heating rates (up to 1 °C/s) (Liu et al., 2015). Most pyrolysis units installed to the date are fixed bed pyrolysis units with slow heating rates. Both, fixed bed pyrolysis and fixed bed gasification processes can be simulated in a laboratory using a bench scale setup (Collot et al., 1999).

2. Methodology

2.1 Sample preparation

MSW samples were collected during the winter sorting campaign in February of 2018. Sampling campaign took place for five days. In total 1,153.18 kg of MSW was sorted for whole sampling campaign. Sorting procedure was carried out in two steps imitating the process of typical MBT plant. During the first step, large objects including recyclables were separated. This part of materials includes categories: paper (Cardboard, Paper, Tetrapack), plastic (HDPE LDPE, PET, other plastic), metals (FE and non FE), glass, wood, textile and leather, Waste Electrical and Electronic Equipment (WEEE), Construction and Demolition (C&D), and others. On the second sorting step, non-recyclables were further sorted. During the second step the remaining material was sorted too, into combustible fraction: mixed paper, mixed plastic, textile & leather and wood. In addition to that, smaller items such as metals (FE and non FE), glass, Waste Electrical and Electronic Equipment (WEEE), Construction and Demolition (C and D), diapers, organics (food waste, green waste, and rest), and fine fraction (< 12 mm) were also sorted. After that, each container was weighed using a digital scale (BEKA 600 kg, deviation 0.2-0.4 kg). During the second step sorting, two samples were retrieved: combustible fraction (mixed paper, mixed plastic, textile & leather and wood) and organics (food waste, green waste, and rest. Hereafter referred to as Org MSW).

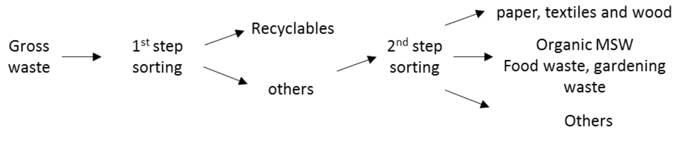

Figure 1: MSW sorting procedure

By mixing and quartering 50 kg of combustible and an Org MSW fractions, representable number of samples were retrieved. Samples were weighed and dried to determine the moisture content. Moisture test was conducted at 105 °C, for the duration of 24 h in a drier (Carbolite RX 60). Then, samples were sterilized in an autoclave at 121 °C.

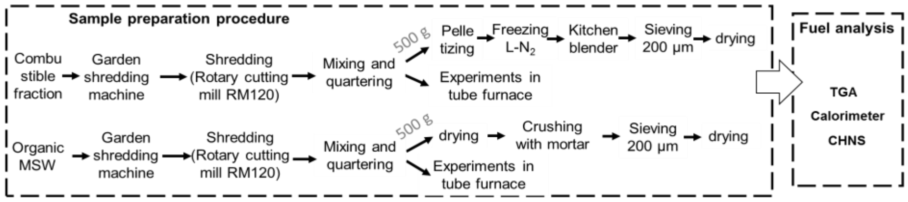

Figure 2: Sample preparation procedure

Retrieved MSW combustible fraction and Org MSW fraction samples had to be processed before analysis. Preparing RDF and Org MSW samples for the analysis is a challenging task itself (Robinson et al., 2016). Sample preparation procedure is schematically described in the Figure 2. Both were first shredded using ordinary garden shredding machine and then shredded further down to a size of 1 mm in a rotary cutting mill. The latest size was suitable for tube furnace experiments but not suitable for laboratory fuel analysis. By mixing and quartering of sample, from each sample, 500 g were taken for further processing and analysis. Coal samples were retrieved by mixing and quartering, then the samples were crushed and sieved through 200-micron sieve for laboratory analysis. Coarse fraction of coal from 1 mm to 1.6 mm in size was used in tube furnace experiments.
Before the experiments, all three, RDF, Org MSW and coal samples were characterized for calorific value in a bomb calorimeter (B-08MA, Etalon, Kazakhstan), proximate analysis (laboratory chamber furnace Carbolite Gero ELF), ultimate analysis in a vario micro cube CHNS analyzer, Elementar, Germany) and thermogravimetric analysis (Q500, TA instruments, USA). Ekibastuz and Shubarkol coal characteristics were also added for comparison. The heating rate of TGA analysis was set to 20 °C/min with a maximum temperature of 900 °C and 20 min hold time.

2.2 Experimental apparatus

The experimental setup is depicted in Figure 3. The furnace is supplied with an air or nitrogen from a gas cylinder. The amount of supplied gas is measured using flow meter. Fixed bed sample was located inside a ceramic tube, which was fixed in the middle of a quartz tube. The diameter of quartz tube is 54 mm and length is 1,000 mm. The weight of sample in each test was 20 ± 1 g. The quartz tube with the fixed sample, is heated in a horizontal tube furnace. Experiments was carried out under nitrogen environment with purity of 99.5 %. Whilst gasification process was maintained under oxygen deficiency conditions at ER from 0.3 to 0.4. Part of outlet gas is diverted to the NDIR gas analyzer (Rapidox 5100B, Cambridge Sensotec, United Kingdom), which has a built-in pump to divert part of the gas flow. Flow rate to the gas analyzer was set to 0.4-0.5 L/min.

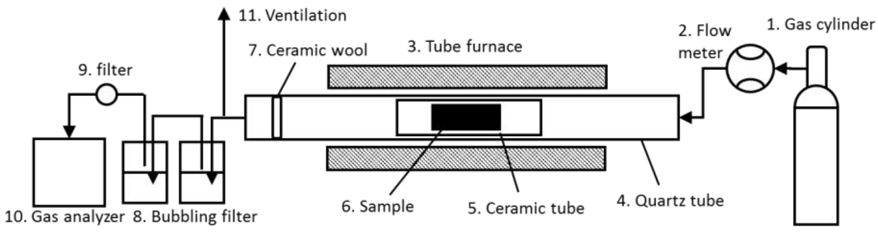

Figure 3: Scheme of the horizontal tube experimental setup

3. Results and discussion

The sorted MSW composition compared with the previous studies are given in the table. As it can be seen from the Table 1, the fraction of Org MSW is high and reaching 43.6 %. The Org MSW can be utilized in a landfill and it can be considered as major source of landfill gas production. In average, 5 % of the total waste can be utilized as RDF, which consists of a degraded mixed paper – 54 wt%, mixed plastics 35 wt%, and wood, textile and leather 11 wt%. The overall experimental procedure was following: heating rate – 20 °C/min, maximum temperature – 800 ºC, time to reach the peak temperature 40 minutes, hold time at maximum temperature – 20 min. The experimental procedure was deliberately chosen to correspond with TGA analysis.

Table 1: Composition of MSW in Astana city

	Paper	Plastic	Textile	Organics	Glass	Metal	Astana city population (Ministry of National Economy, 2018)
2006 (Inglezakis et al., 2017)	25.9	14.8	3.85	28.9	3.3	4.35	550,438
2012 (Ministry of regional development, 2012)	13	18.5	9.8	28	14.5	0.9	742,918
2018 February	11.7	13.2	2.7	43.6	5.8	2.2	1,029,556

Figure 4 represents the thermogravimetric curve for RDF and Org MSW in nitrogen environments. Both plots well reflect their proximate analysis as shown in Table 2. It can be noticed that decomposition of RDF starts rapidly by losing its mass at temperatures above 230-240 °C and its conversion reaches peak at 320-340 °C. Whilst the Org MSW started to react at 170-180 °C. Org MSW peak of conversion was at 150-200 °C. RDF sample completely devolatilized at the temperature of 700 °C. However, the Org MSW still kept some of its volatiles at 700 °C. Org MSW was fully devolatilized at the temperature range of 850-880 °C.

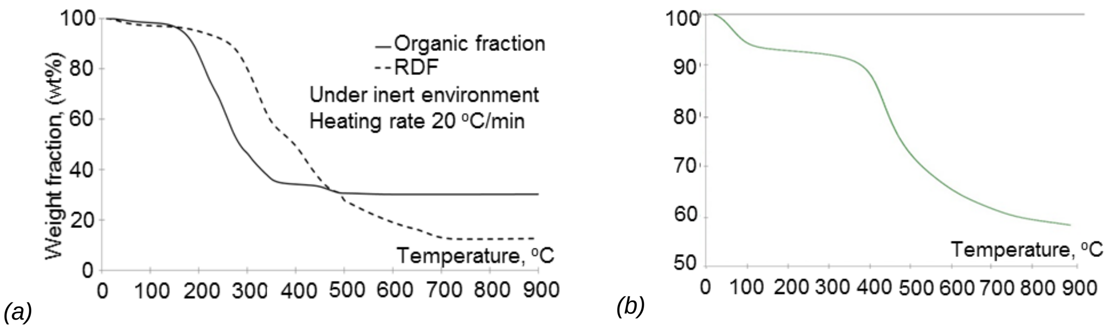

Figure 4: (a) RDF and Org MSW, (b) Shubarkol coal samples TGA analysis in N_2

Table 2: Proximate and ultimate analysis of RDF and Org MSW

Proximate (as received wt%)	RDF-Astana (Sarbassov, 2018)	Org MSW - Astana	Ekibastuz	Shubarkol
Ash	12.3 ± 3.64	20.3 ± 1.29	38.54	2.44
Moisture	4.6 ± 0.55	4.4 ± 0.55	1.31	5.96
Volatile matter	81.6 ± 2.64	65.2 ± 1.31	19.94	40.3
Fixed carbon	4.2 ± 1.2	3.5 ± 0.55	40.21	51.3
Ultimate (dry ash free wt%)				
C	47.6	46.16	77.82	69.72
H	5.84	6.23	5.03	6.05
N	2.58	4.18	2.22	1.71
S	0.26	0.26	1.04	1.05
O (by difference)	43.7	43.17	13.89	21.47
Gross calorific value, MJ/kg	17.44	17.77	19.37	26.97

Figures 5 and 6 represents the exit gas composition during the tests. x-axis of the plots represent time of the experiment. This also corresponds to the heating up period with the heating rate of - 20°C/min. Y-axis represents volumetric concentration of pyrolysis gases. Figure 5 and 6, represents the experimental results under pyrolysis and gasification of samples. As it can be seen from the TGA plot (Figure 4) mass loss is observed at temperatures below 500 °C, but according to Org MSW pyrolysis (Figure 5) products were registered above 500 °C. The mass loss of Org MSW at the temperature range from 200 °C to 500 °C can be explained by cracking of solid hydrocarbons to condensable long chain hydrocarbons such as tars.
In this test, long chain hydrocarbons were trapped by gas washers and did not reach the gas analyzer. Condensable long chain hydrocarbons cracked at temperatures above 500 °C. Cracking of these non-condensable substances released high yields of oxygen which then react with carbonaceous materials from the fuel and increase the yield of CO and CO_2. Similar process was reported by Figueroa et al. (2015) during pyrolysis of sugarcane bagasse in fixed bed. Synergetic effect was also observed by Seo et al. (2010). Seo observed activation energies of RDF and coal are lower when blended in 50 % ratio.

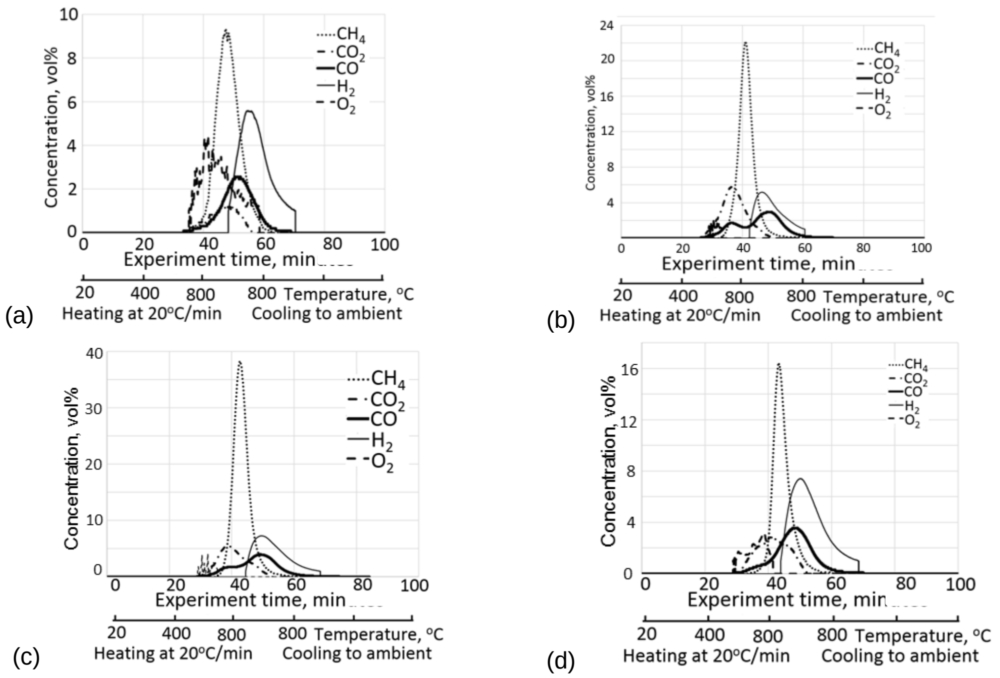

Figure 5: Horizontal tube furnace experiments in nitrogen. (a) 20 g Org MSW in N2, (b)15 g Org MSW and 5 g coal, (c)10 g coal and 10 g Org MSW, (d)15 g coal and 5 g Org MSW

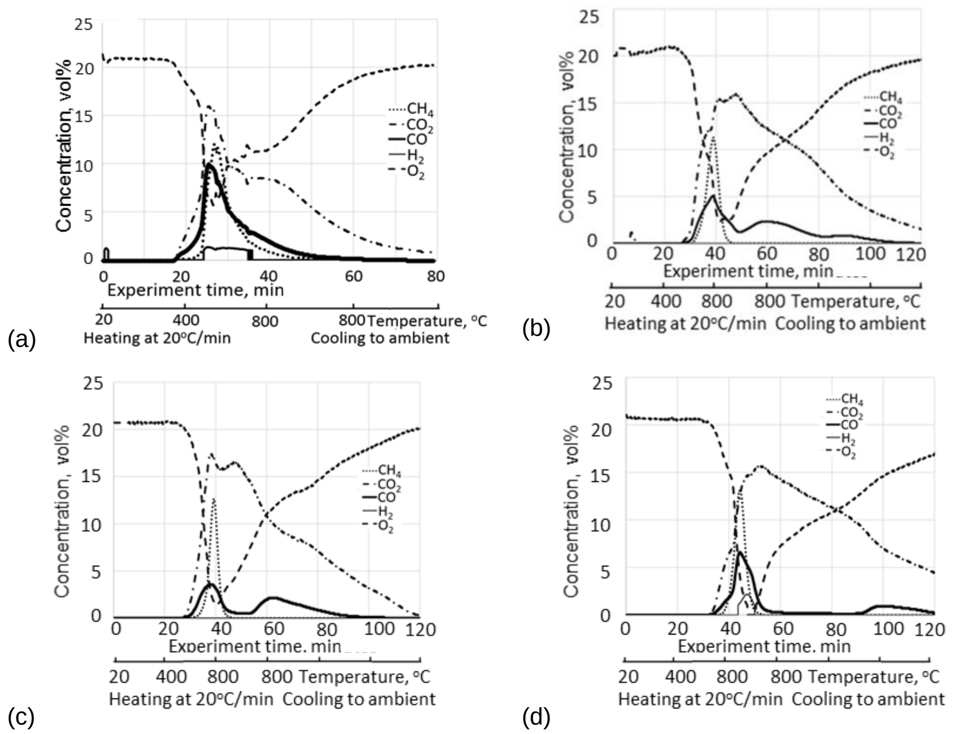

Figure 6: Horizontal tube furnace experiments in air. (a) Org MSW in Air (b) 10 g coal + 10 g Org MSW in Air (c) 5 g coal+15 g Org MSW in Air (d) 15 g Coal + 5 g Org MSW in Air

Methane release is registered at the maximum temperature, during holding it at 800 °C and 50 % Org MSW blend. Hydrogen release can be increased with injection of water and reaction of hydrocarbons with steam (Streitwieser and Cadena, 2018). Gasification products have not been registered at temperatures below 500 °C, and the reason could be due to the condensation of tars. This phenomenon needs to be investigated further through capturing of tars in a solvent and further analysis using a gas chromatography and mass spectrometry.

Guan et al. (2009) also observed significant reduction of tar yield and increase of gas yield when MSW/biomass gasification reactor temperature increased from 600 °C to 900 °C. Guan et al., also observed higher yield of hydrogen during steam gasification of MSW due to steam reforming (Guan et al., 2009).

4. Conclusion

The MSW composition during winter season has been determined from Astana city. The share of Organic fraction in MSW is found high of 43.6 %. Separation of the recyclables and RDF production in Astana can potentially reduce the total stream of waste up to 50-56 %. The remaining amount can be efficiently landfilled or composted. High moisture content of Org MSW makes allothermal processes costly and requires valorization before the process. However, co-gasification with coal can be another feasible solution to avoid costly allothermal processes. MSW and coal blend pyrolysis demonstrated higher synergetic effect and increased yields of methane compared to Org MSW pyrolysis and gasification. For fixed bed process, the desirable temperature is found between 750-800 °C. Blending of Org MSW and coal resulted in higher yields of methane, which can be explained by depletion of oxygen reacting more with CO and H_2 rather than with CH_4. Coal pyrolysis typically produce higher yields of CO and CO_2 rather than CH_4 and H_2. It is necessary to mention that Org MSW taken from the MBT plant has plastics, paper, textile, and wood that couldn't be retrieved, and their presence greatly increases methane and tar yields.

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