Improved solutions for solid waste to energy conversion

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Abstract: The paper presents the results of different solid waste properties analysis with respect to energy potential and combustion characteristics. The research focused on products physical-chemical properties quantification by experimental approach: primary analysis and elemental analysis. The analyses were performed on heterogeneous solid waste cellulose and organic based. The volatile / fixed carbon content, inert fraction and polluting elements were quantified. The research offers energy conversion solutions for a large series of solid heterogeneous wastes unfitted for direct combustion, using advanced thermal processing: pyrolysis, pyrocombustion and pyro-gasification. The influence of pre-treatment process parameters on by-products was investigated to optimize the pyrolysis sequence with respect to global energy efficiency. The aim was the identification of a set of operating parameters for pre-treatment process for minimum energy consumption and the integration of this sequence in the global energy recovery chain.

Keywords: Waste, Energy, Thermal processes.

1. Introduction

A promising option as renewable energy source is the production of hydrogen rich gases from solid waste such as biomass or non-recyclable plastic products. One source of hydrogen could be the direct release of the hydrogen chemically bound in the waste as part of any thermal degradation process under inert atmosphere, the pyrolysis process. The second source of hydrogen is the steam gasification of carbon or hydrocarbons as part of the feedstock or primary thermal treatment under pyrolysis conditions [1]. As renewable surface fuels such as biomass and most types of refuse are occurring in a widespread and diffuse way, decentralized low and medium scale power units technologies are needed for the energy conversion. The low and medium scale power units present major disadvantages if common combustion process is used. The main cause of the incineration global energy efficiency limitation is the high excess air required for the complete wastes oxidation, especially for heterogeneous type waste. For waste with low combustibility properties or heterogeneous composition the integration of pyrolysis stage into waste-energy chain provides advantages with respect to product physical-chemical structure and properties. A solution for continuous operated power plant could be combustion, preceded by product pre-treatment for the decrease of high moisture content and fast degradation properties. The stabilization of the product, through pyrolysis process, can solve the ignition problems, the combustion process stability (decreasing the pollution emissions) and medium/long term storage of the waste (in industry sector where the waste availability can be discontinuous this could solve the continuous operation of the power plant). The pyrolysis stage within waste to energy combustion chain provides a series of advantages with respect to raw product properties by transforming it into high carbon content derived fuels [2].

The paper presents an example of using pyrolysis process for the conversion of agriculture and food industry waste into derived fuels together with the identification of optimum process parameters, to maximize the derived fuels energy potential in terms of global energy balance. The sample mass decreasing rate during the process run is determined to establish the product behavior under non-oxidant conditions at atmospheric pressure with respect to process kinetics.

2. Experimental setup

2.1. Installation

For the pyrolysis process configuration a tubular electric Nabertherm reactor was used. The reactor was modified according to experiment set-up within Laboratory of Renewable Energy Sources of Polytechnic University of Bucharest. Laboratory scale reactor consists of a refractory stainless steel tube, exterior electrically heated and with an interior diameter of 60 mm. Active heating area has a length of 750 mm. Horizontal tube furnace is equipped with two outlet tubes made for gas and liquid discharges resulted from treatments applied to solid masses. Two inlets are also present (position 1 and 2 on Fig. 1.) for treatment gas injection. Schematic diagram of the main elements of fixed bed furnace is shown in the figure below.



 Nitrogen injection; 2. Air injection; 3. Refractory steel crucible; 4. Refractory steel tube;
Electrically heated chamber; 6. Exhaust gases; 7. Thermocouple; 8. Liquid reaction products (tar); 9. Sample

Fig. 1. Tubular batch reactor.

Working temperature range is between 20°C to 1300°C. Pyrolysis device is equipped with a control pad that allows temperature programming, working time (residence time at process temperature) and heating rate. Samples to be subjected to treatment processes are introduced into the furnace in a tubular parallelepiped crucible of refractory steel. To ensure an inert atmosphere in the oven during the pyrolysis process, nitrogen was blasted, its flow being measured using a flow controller.

2.2. Products

The material used in this study is represented by a large category of heterogeneous solid waste: cellulose based waste (paper, cardboard, package), agriculture waste and food industry. The moisture content determined for the materials as arrived varied between 8% and 70%. Different analyses were performed on the dried products: proximate analysis, elemental analysis, high heating value determination. For the determination of volatile content the temperature was set at 800°C and the crucible with material previously graded, stayed in the oven for 40 minutes. The samples obtained in the first stage are subjected to a combustion process in order to determinate the total content of the combustible materials, respectively the one of inert (non-combustible). Results are presented in the table below.

Table 1. Proximate analysis of waste products.

Product	Volatile [%]	Fix Carbon [%]	Inert [%]	
Cellulose based waste	87.5	6.6	5.9	
Food industry waste	91	7.5	1.5	
Agriculture waste	74	21	5	

The chemical composition of the materials was established using an elemental analyzer, with a sample weight which varied around 1 mg. The EA 3000 Series used analyzer uses the principle of dynamic flash combustion followed by gas chromatography separation of the resultant gaseous species (N2, CO2, H2O, and SO2) and TCD detection (Table 2).

Table 2. Elemental analysis of waste products.

Product	C [%]	H [%]	N [%]	S [%]	Cl [%]	O [%]	A [%]
Cellulose based waste	36.8	5.1	0.1	0.2	0.1	35.4	5.9
Food industry waste	60,6	8,5	8,7	4,8	2.6	13,3	1.5
Agriculture waste	48.1	5.4	1.4	3.7	0	36.3	5

It can be concluded that the characteristics of these wastes are similar to different types of wood biomass when we refer in particular to volatile content and elemental composition.

3. Results and discussions

3.1. Process run

Current pyrolysis experiments are conducted under controlled heating rate. In industrial applications this is practically impossible because the product is introduced directly in the reactor from environment temperature to process one. Therefore the heating rate is maximum given by the difference between these two temperatures under the specific heat transfer process within the product, depending on reactor type. The pyrolysis process was conducted in the tubular batch reactor, each product sample being exposed to a specific temperature in the preheated furnace, hence subjected to a flash pyrolysis similar to industrial operating conditions [2].

The mass of each sample varied between 50 and 60 grams depending on products specific weight. In this case the mass was considered quasi-constant and in a significantly small quantity suited for the crucible. Nevertheless the conditions encountered in an industrial process are different from experimental size units, such as the one in case, because heat and mass transport mechanisms will influence the process by-products fraction rate and properties, but the variation tendencies remain the same.

The flow of nitrogen into the reactor was $100 \text{ cm}^3/\text{min}$ and the heating rate approximately 40 - 50 °/min. For the cellulose based products (agriculture waste included) the range of temperature varied between 350°C and 600°C. For the food industry waste, due to product specific structure (high keratin content), the temperatures chosen were between 450°C and 800°C [3].

In order to determine the residence time of the material to be subjected in the tubular reactor, the product was first treated by the same thermal pyrolysis process in an electric furnace, connected to a high precision balance. The mass variation of the samples was observed through the pyrolysis process (Fig. 2).



Fig. 2. Sample mass variation during pyrolysis processing.

The product undergoes three stages: heating, devolatilization, char stabilization. When the material's mass stops varying, it ceases to release volatiles and the process is completed. Based on first experimental results the residence time for a complete pyrolysis process was established at 40 minutes. The collecting tube for the liquid reaction products allows the entire heavy hydrocarbons and water fraction to condense, being collected at the end of the tube in a container as tar.

3.2. Results

The heterogeneity of waste imposed the separation of pyrolysis experiments. The cellulose based waste (paper, cardboard, package) and the biomass (mix of agriculture waste) were treated separately at low and medium temperatures [4]. The food industry waste was submitted to medium and high temperature treatment. The results showed similar behavior of the samples and process by-products for the same treatment temperature. Results regarding the production of these three derived fuel are presented in Fig. 3 and Fig. 4.



Fig. 3. Tar, char and gas variation during cellulose based products and biomass pyrolysis.

For all products the maximum yield of tar is found at temperatures between 500°C and 600°C, after this temperature it is observed a decrease of the compound. This may be due to secondary reactions in the gas phase which are very fast, leading to over cracking of the products formed, and reducing the liquid yield. On the other hand, lower temperatures prevent the full decomposition of the biomass. In addition, the solid char yield decreases with increasing pyrolysis temperature.



Fig. 4. Tar, char and gas variation during food waste products pyrolysis.

It is observed that once the temperature increases, the product releases volatiles faster, hence a decrease in the mass of char left in the crucible. The char yield decreases with 18 percentage points as the pyrolysis temperature was increased from 350°C to 600°C. The decrease in the char yield with increasing temperature could be due either to greater primary decomposition of biomass at higher temperature or through secondary decomposition of the char residue [5], [6].

The secondary decomposition of the char at higher temperatures may also give some noncondensable gaseous products, which also contributes to the increase in gas yield [7].

An optimum valorization of these derived products requires the maximum energy potential of the by-products for the minimum energy consumption during the pyrolysis stage treatment. Using calorimetric determination for each solid and liquid by-product and the mass fraction the energy potential of the derived fuels was estimated. For all products the maximum low heating value (LHV) of the char was achieved at low temperatures 350° C, respectively 450° C – approximately 27000 kJ/kg. The tar LHV was maximum at 550° C and 600° C – 24000 kJ/kg. For the biomass products after $500 - 550^{\circ}$ C, a low drop of LHV was determined. The corresponding increase in fixed carbon and ash content with temperature is due to removal of volatile matter leaving the more stable char and ash-forming inorganic matter in the biomass. The same evolution was encountered for the industry waste after 600° C.

The maximum energy potential of pyrolysis by-products is achieved at different temperatures therefore the option for a specific temperatures strongly depends on next energy conversion chain. In case of pyro-combustion-steam turbine cycle the influence of pyrolysis temperature on global energy efficiency is minimum (with respect to by-product mass fraction ratio and LHV) therefore the lowest temperature is preferred due to energy consumption of this treatment stage (350°C - 400°C). With respect to product heterogeneous structure, even if during the pyrolysis stage the energy consumption represents a loss for the global efficiency, the homogenous physical-chemical structure of the by-products can be used in combustion efficiency increase. Higher efficient combustion equipment can be used (pulverized combustion, fluidized bed) replacing the non-efficient grille bed combustors. The energy loss in pyrolysis stage can be recovered by the increased efficiency of the combustion stage. A higher combustion temperature enables higher steam parameters and higher steam turbine cycle efficiencies [8]. In case of pyro-gasification-gas turbine/engine cycles the influence of pyrolysis temperature on global energy efficiency is maximum (with respect to by-product mass fraction ratio and LHV). The gasification stage requires maximum amount and LHV of char to be gasified. The technological solution, in this case, is the one that imposes the pyrolysis stage temperature. Porosity quantification of char is also needed due to air/steam char reactivity. Further experiments are now in progress.

4. Conclusion

The paper presents the results on thermal-processing for energy recovery of heterogeneous solid waste using non-oxidizing stage as pre-treatment. The research focused on products physical-chemical properties quantification by experimental approach: primary analysis and elemental analysis. The analyses were performed on heterogeneous solid waste cellulose and organic based. The pyrolysis experiments revealed that similar products (as chemical composition) with different physical structure generate different by-products under the same treatment conditions. Based on first experimental results the residence time for a complete pyrolysis process was chosen of one hour.

For all products the maximum yield of tar is found at temperatures between 500°C and 600°C, after this temperature it is observed a decrease of the compound. It is observed that once the temperature increases, the product releases volatiles faster, hence a decrease in the mass of char left in the crucible. Using calorimetric determination for each solid and liquid by-product and the mass fraction the energy potential of the derived fuels was estimated. For all products the maximum low heating value of the char was achieved at low temperatures 350°C, respectively 450°C. The tar LHV was maximum at 550°C and 600°C. In case of pyro-

combustion-steam turbine cycle the lowest pyrolysis temperature is preferred due to energy consumption of this treatment stage ($350^{\circ}C - 400^{\circ}C$).

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