Journal of Analytical and Applied Pyrolysis 105 (2014) 234–240

Contents lists available at ScienceDirect

Journal of Analytical and Applied Pyrolysis

journal homepage: www.elsevier.com/locate/jaap

Influence of the microwave absorbent and moisture content on the microwave pyrolysis of an organic municipal solid waste

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ARTICLE INFO

Article history:
Received 30 September 2013
Accepted 17 November 2013
Available online 23 November 2013

Keywords:
Microwave absorbent
Pyrolysis
Municipal solid waste
Syngas
Waste valorisation

ABSTRACT

Microwave pyrolysis is presented in this study as a recycling approach for municipal solid waste treatment. The process is based on the conversion of solid waste to syngas ($CO + H_2$) by means of a microwave absorbent. Experiments to characterise the syngas produced were performed using the char obtained from the pyrolysis of a municipal solid waste as microwave absorbent in the microwave power range of 150–450 W and in an absorbent-to-waste ratio range of 0.2:1 to 1:1 (wt.%:wt.%). A rich-syngas fraction with a high H_2 content (c.a. 50–55 vol.%) was obtained and analysed by means of response surface methodology through the interaction between the microwave power and absorbent-to-waste ratio. Moreover, a positive effect of the moisture content on gas production is attained since gasification of the char occurs. Thus, the simple use of a cheap waste-derived char leads to a reduction in the microwave power and economic cost of the process.

1. Introduction

Municipal solid waste (MSW) consists mainly of waste from households (60–90%), though similar wastes from other sources such as commerce or public institutions are also included. According to Eurostat, which is the statistical body of the EU, MSW generation in Europe has remained stable at about 260 Mt per year since 2002 [1]. Various management alternatives are available for the treatment of MSW such as landfilling, incineration, recycling or composting. In recent years, recycling has increased, although landfilling still remains the most widely used method of disposal, in spite of its several drawbacks, such as the leaching of dangerous chemicals into the soil and the release of methane to the air. However, this gap has narrowed in the last few years. In the EU the landfill/recycling MSW weight ratio was 56/17 in 2001 compared to 37/25 in 2011 [2].

Pyrolysis technology has emerged not only as a very effective way of MSW disposal but also as an attractive technology for valorising these residues by producing fuels or precursors of valuable chemicals, such as syngas ($CO + H_2$). As an example, the SYNPOL project [3] aims to produce new biopolymers via the fermentation of syngas from waste materials.

Several studies have been carried out on MSW pyrolysis [4–7]. In general, the syngas content of the gas fraction produced in pyrolysis processes is not very high, since it is mixed with large amounts of CO_2, CH_4 and light hydrocarbons. As a way to improve the syngas concentration and, especially, the H_2 content, several researchers have proposed catalytic pyrolysis. In such cases, the role of the catalyst, such as dolomite [4], is to crack the heavy compounds in order to obtain lighter gases. However, the same effect can be achieved by means of microwave irradiation, without the need to add a catalyst to the system, as demonstrated in previous studies [8–10]. Microwaves are able to generate microplasmas, which promote heterogeneous catalytic reactions, but not all materials can be heated by means of microwave irradiation, since some materials are transparent to microwaves. To solve this problem, the addition of carbon-rich materials has been proposed to absorb microwaves [11–14]. The material to be pyrolysed is then heated by conduction. Use of the char obtained from MSW pyrolysis process, as microwave absorbent is an attractive solution since it avoids the addition of materials that might increase the cost of the process.

The microwave pyrolysis of MSW has been performed previously by Gedam and Regupathi [15], but it is still at an early stage of development. In the study of Gedam and Regupathi, both the microwave power and irradiation time were varied. Although a minimum value of power was required to carry out the pyrolysis of MSW, the addition of different carbon materials that served as microwave absorbents allowed the pyrolysis to proceed at a lower microwave power. Surprisingly, no hydrogen was produced other than trace concentrations, providing a gas rich in CO, CO_2 and CH_4. So far the effect of the amount of microwave absorbent on MSW pyrolysis has not received much attention. However, this parameter has been studied in relation to other materials. The microwave

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0165-2370/$ – see front matter
http://dx.doi.org/10.1016/j.jaap.2013.11.009

induced pyrolysis (MIP) of microalgae with various microwave absorbents, such as activated carbon, CaO, SiC or microalgae char has been carried out by Hu et al. [16]. These authors found that there was a specific proportion of absorbent-to-microalga at which the liquid fraction was maximised, depending on the absorbent used. Oil palm shell biomass was recently subjected to MIP in a study by Salema and Ani [17], which showed the importance of the quantity of microwave absorbent added to the oil palm shell as a method of controlling the pyrolysis temperature in an overhead stirrer reactor. The authors reported that an increase in microwave absorbent led to a decrease in the pyrolysis temperature and in turn in to higher solid fraction yields. All of these studies were focused on maximising the liquid fraction yield. However, to the best of our knowledge, no studies have been aimed at maximising the gas fraction yield.

Herein, we report for the first time on a statistical model based on response surface methodology (RSM) designed to assess the combined effect of microwave power and ratio of microwave absorbent-to-waste upon the amount and characteristics of the syngas generated from MIP. In addition, the effect of moisture content of the MSW is evaluated.

2. Materials and methods

2.1. Materials

The sample selected for this study was an organic fraction from a municipal solid waste, supplied by BEFESA *Gestión de Residuos Industriales* S.L. (Seville, Spain) in two forms: wet (with a moisture content of c.a. 45 wt.%) and dry (with a moisture content of c.a. 1.5 wt.%). The dry and wet fractions will be labelled as *D* and *W*, respectively. Proximate and ultimate analyses were performed to characterise the composition of the feedstock samples. The moisture, ash content and volatile matter data (from a LECO TGA-601) are summarised in Table 1 together with the ultimate analysis results (a LECO-CHNS-932 micro-analyser and LECO-TF-900 furnace were used). Metallic content of the ashes from the organic MSW was determined by means of atomic absorption spectroscopy.

The gases were analysed in a Varian-CP3800 gas-chromatograph equipped with a TCD detector and two columns connected in series. The first column was 80/100 Hayesep Q (2 m × 1/8 in. × 2 mm) and the second column was 80/100 Molesieve 13× (1.5 m × 1/8 in. × 2 mm). The second column was bypassed by a six-port valve for the analysis of CO_2 and hydrocarbons. The TCD was calibrated with a standard gas mixture.

2.2. Microwave induced pyrolysis

The pyrolysis of *D* and *W* was carried out in a microwave oven which consisted basically of a microwave magnetron with a maximum output power of 2 kW operating at 2450 MHz and a single mode cavity where the sample was irradiated using powers ranging from 150 to 450 W. The single mode cavity allows a well-defined electric field in a relatively small volume due to the superposition of incident and reflected waves, and causes the microwave field to focus on a given location [18]. The reflected power is regulated until it is reduced to zero by means of stub tuners. About 3 g of sample (on a dry basis) was placed on an inert bed inside a quartz reactor. The reactor was purged with N_2 for 30 min at a flow rate of 50 mL_{STP} min^{-1}. The N_2 flow rate was then set to 10 mL_{STP} min^{-1} for the pyrolysis experiments in order to ensure an oxygen-free atmosphere.

As mentioned in previous studies on microwave induced pyrolysis of biomass, it is also necessary to mix the MSW fraction with an appropriate microwave absorbent to achieve the high temperatures required for pyrolysis [11–14]. The char obtained from the prior pyrolysis of *D* and *W* at 800 °C in an electrical furnace was used as microwave absorbent in different absorbent-to-waste ratios (0.2:1, 0.4:1 and 1:1), in order to evaluate the influence of this parameter on the characteristics of the syngas. Preliminary experiments showed that lower values of absorbent-to-waste ratio prevented the pyrolysis of the MSW fraction.

The experiments lasted 1 h, but the time chosen for the calculation of the parameters was 40 min, since by this time all the MIP experiments would have reached 90% of total syngas production.

The volatiles released from the pyrolysis of both organic fractions were passed through a condensing system cooled by a cryogenic solution of water and NaCl. The liquid fraction was recovered from the condensing system by dissolving it in CH_2Cl_2. It was then subjected to further evaporation to remove the solvent at 40 °C. The non-condensable gases were collected at intervals of 10 min in Tedlar sample bags and then analysed by gas chromatography. The composition of the gaseous fraction was determined from the composition of each bag and the N_2 flow rate.

2.3. Statistical model

RSM is a widely used technique for the optimisation of a set of parameters. This methodology assesses the combined effect of a set of independent variables on response variables by means of three-dimensional surface plots. The experimental response variables are fitted to a mathematical model by multiple regression analysis, which is then subjected to statistical evaluation by means of the analysis of variance (ANOVA) in order to determine whether the model and model parameters are significant on the basis of the *p*-value to within a certain level of confidence, e.g. at 95%. In the field of MIP, only a few studies employ RSM [19,20], but none of them are focused on the influence of the microwave power or on the effect of the microwave absorbent on the syngas produced.

As mentioned at the end of Section 1, three factors were selected as the independent variables used to model the characteristics of the gas obtained from the MIP of the organic fraction of municipal solid waste: the microwave power (*P*, expressed in Watts), the absorbent-to-waste ratio (*A*, wt.%:wt.%) and the moisture content (*M*, wt.%). The values of *P* ranged from 150 W to 450 W and those of *A* from 0.2:1 to 1:1. Additional experiments were performed on the *W* fraction (45 wt.% of moisture) to evaluate the influence of the water content on the pyrolysis process.

In order to model the gas fraction evolved during the MIP, the following response variables were characterised: the syngas concentration, i.e. CO + H_2 concentration in the pyrolysis gases (*S*, vol.%); the syngas production (SP, L_{STP} $g_{MSW}{}^{-1}$) and the H_2, CO, CO_2 and CH_4 concentrations in the gas fraction (vol.%). The experimental design is shown in Table 2.

The experimental results for *D* and *W* were fitted using a polynomial quadratic equation (Eq. (2.1)) by means of Design Expert® software to correlate the response variables *R*(*P*, *A*) to the independent variables *P* and *A* within the model parameters: the offset term (α), the linear effects (β, γ) the squared effects (δ, ε) and the interaction term (ζ):

$$R(P,\ A) = \alpha + \beta P + \gamma A + \delta P^2 + \varepsilon A^2 + \zeta PA \quad (2.1)$$

3. Results and discussion

3.1. Syngas production models

The main objective of this study is to characterise the syngas generated by the microwave induced pyrolysis of municipal solid waste and determine its composition and production. The