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Demonstration of the waste tire pyrolysis process on pilot scale in a continuous auger reactor

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HIGHLIGHTS

- The continuous pyrolysis of waste tire has been demonstrated at pilot scale in an auger reactor.
- More than 500 kg of waste tires were processed in 100 operational hours.
- The yields and characteristics of the pyrolysis products remained constant.
- Mass and energy balances for an industrial scale plant are provided.
- The reaction enthalpy necessary to perform the waste tire pyrolysis was determined.

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ABSTRACT

This work shows the technical feasibility for valorizing waste tires by pyrolysis using a pilot scale facility with a nominal capacity of 150 kW_{th}. A continuous auger reactor was operated to perform thirteen independent experiments that conducted to the processing of more than 500 kg of shredded waste tires in 100 h of operation. The reaction temperature was 550 °C and the pressure was 1 bar in all the runs. Under these conditions, yields to solid, liquid and gas were 40.5 ± 0.3, 42.6 ± 0.1 and 16.9 ± 0.3 wt.% respectively. Ultimate and proximate analyses as well as heating value analysis were conducted for both the solid and liquid fraction. pH, water content, total acid number (TAN), viscosity and density were also assessed for the liquid and compared to the specifications of marine fuels (standard ISO 8217). Gas chromatography was used to calculate the composition of the gaseous fraction. It was observed that all these properties remained practically invariable along the experiments without any significant technical problem. In addition, the reaction enthalpy necessary to perform the waste tire pyrolysis process (907.1 ± 40.0 kJ/kg) was determined from the combustion and formation enthalpies of waste tire and conversion products. Finally, a mass balance closure was performed showing an excellent reliability of the data obtained from the experimental campaign.

1. Introduction

Management of used tires has become a serious environmental problem. The remarkable increase in the number of vehicles worldwide and the lack of both technical and economical mechanisms as well as specific legislations for addressing the waste disposal problem make that many waste tires are disposed in dumps. Rubber from tires can be considered as both a non-destructible and non-biodegradable material since they are designed to withstand harsh mechanical and weather conditions as ozone, light and bacteria among others. Therefore, the management of used tires represents a serious technological, economic and ecological challenge [1]. It is estimated that approximately one used tire per capita and per year is produced in the developed countries [2], and that 4 billion of tires are currently in landfills and stockpiles worldwide [3]. These dumps represent a serious threat to both the environment and human health because they are favoring the growth of pests and insects, causing not only a high risk of fire, which in turn can be difficult to extinguish, but also an environmental impact due to uncontrolled emissions of potentially harmful compounds into the atmosphere, soil and groundwater.

Tires are mostly composed of different rubbers, such as natural rubber (NR), butyl rubber (BR), and styrene-butadiene rubber (SBR), as well as mineral oils and carbon black (CB) [4]. Since rubber from tires have a heating value even higher than coal (around 35,000 kJ/kg) as well as considerable amount of CB (around

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35–40 wt.%), it seems reasonable to find a route to take advantage of its high energetic and raw material potential in order to progress in the search of alternative fuels, CO_2 emission mitigation and the reduction/recycling on raw materials from unconventional sources. Pyrolysis as an attractive method to recycle scrap tires has recently been the subject of renewed interest [5–7], and it has many advantages to tackle the waste tire disposal problem compared to other thermochemical processes such as combustion and gasification. Apart from enable CB recuperation (trapped in the char fraction), the volatile matter released (condensable and non-condensable compounds) has the potential of renewable energy recovery because of the NR present in the tire. Besides, it is noteworthy the transformation into a liquid fuel that can be easily handled, stored and transported, allowing a significant flexibility for future power or thermal applications. In fact, liquid from waste tire pyrolysis is completely miscible with petroleum diesel [8] and some works using blends of both fuels in existing compression ignition engines can be found in the literature [9–11].

Waste tire pyrolysis has received special attention from 1990s, although since late 1960s a notable number of projects with a broad range of technologies and scales can also be found in the literature [12]. Several studies have been performed to investigate the influence of temperature, pressure, heating rate and both volatiles and solid residence time on the product yields and characteristics using different types of reactors [12]. However, up to now, it has not been applied to an extensive industrial scale, due to the lack of products standardization and available markets (for both the solid and liquid fraction), legislative barriers (it is considered as incineration in the EU) and, sometimes, public acceptance [13]. Products from waste tire pyrolysis are more complex from the physical–chemical point of view than products from other thermochemical processes. The absence of a wide market for the solid fraction has caused that waste tire pyrolysis is not yet industrially widespread. In fact, the European Tire Rubber Manufactures' Association (ETRMA) in a recent report [14] refers to pyrolysis as an emerging technology, since its economic viability has yet to be proven (there are few or no large-scale plants currently in operation).

At present, waste tire pyrolysis is mainly engaged in research purposes. There is available literature on continuous and semi-continuous tire pyrolysis processes at both pilot and laboratory scale using different technologies such as rotary kiln [6,15], both bubbling [16] and circulating [17] fluidized bed reactors, vacuum moving bed reactor [18], fixed-bed reactor with both fire-tube heating [8] and electrical heating [4,19], conical spouted bed reactor [20] and auger reactor [2,21] among others. However, technical information and testing data from long-term experiments are quite scarce in literature. Hence, this work is important because it reports results obtained continuously in a pilot reactor (150 kW_{th}), which serves as a bridge for designing large-scale plants. The process stability is assessed both in terms of product yields and characteristics. To the best of authors' knowledge, this is one of the first studies investigating a pilot and continuous pyrolysis reactor with respect to its stability and reproducibility in an experimental campaign of more than 100 accumulated hours of operation. Hence, the purpose of this study is to provide reliable results aiming at the process scaling-up.

2. Materials and methods

2.1. Feedstock

The raw material used in all the runs consisted of a non-specific mixture of granulated waste tires (particle size between 2 and 4 mm) supplied by a Spanish waste tire recycling company. The waste tire scraps were composed of rubber without both the steel thread and the textile netting. The ultimate analysis was carried out in a Carlo Erba-1108 instrument, the moisture and the ash contents were measured according to ISO 589-1987 and ISO 1171-1976, respectively; while the volatile matter was determined according to ISO 5623-1974. The heating value was measured experimentally with a calorimetric bomb IKA C-2000 and determined according to ISO 1928-76. In addition, three devolatilization experiments from room temperature up to 700 °C at 5, 10 and 20 °C/min, were performed in a thermobalance Setaram Setsys system. The sample weight used in all experiments was 20 mg and the carrier gas was N_2 at 150 mL_N/min.

2.2. Auger reactor

The pilot plant used in this research was described in detail elsewhere [2,21]. It comprises four main parts: the feeding system, the reactor, the vessel for solids collection and the condensing system. Both the feeding system and the reactor consist of worm screws. Pyrolysis reactor is heated by external electrical furnaces and three thermocouples measure the temperature profile along the reactor. During reaction, waste tires move through the reactor while decomposing into a solid residue and volatiles. Whilst the volatile fraction reaches two consecutive heat exchangers by natural convection with the help of the carrier gas, the solid residue leaves the reactor falling down by gravity into a vessel for solids collection. In both condensers, the condensed fraction is recovered in a liquid collector after moving down by gravity. Finally, the non-condensed gas fraction at ambient temperature is conducted to a burner before reaching the atmosphere. The reactor is able to process up to 15 kg/h of wastes tires and this supposes a nominal thermal inlet power of around 150 kW_{th}.

2.3. Experimental procedure

The influence of the main pyrolysis process variables involved in the auger reactor (temperature, solid residence time, mass flow rate and inert gas flow) has been published elsewhere [2,21]. Since this work deals with the demonstration of the waste tire pyrolysis process on pilot scale to provide reliable results aiming at the process scaling-up, all the experiments were carried out at 550 °C and atmospheric pressure using N_2 as carrier gas at 5 L_N/min. The waste tire mass flow rate was 6.7 ± 0.1 kg/h. The residence time of the feedstock inside the reactor was fixed in 3 min by adjusting the rotation speed of the screw located inside the reactor. These variables were selected as those maximizing both the liquid yield and the tire rubber conversion. Yields to solid and liquid products were directly obtained by weight while the yield to gas was calculated by difference. Both liquid and non-condensable gas samples were taken once the steady state was reached, approximately after 30 min from the beginning of the experiment. Thirteen runs were performed and a total of 560 kg of waste tires were processed. Around 100 h of continuous operation without any technical problem were accumulated.

2.4. Product characterization

The solid fraction (also known as char or pyrolytic carbon black) was characterized by measuring its heating value (IKA C-2000) according to UNE-EN 15400, as well as by both ultimate (Carlo Erba-1108) and proximate analysis (moisture from UNE-EN15414-3, ash from UNE-EN 15403 and volatile matter from UNE-EN 15402). The liquid fraction obtained in all the runs was characterized by ultimate analysis (Carlo Erba EA1108), heating value (IKA C-2000) according to ASTM 240-09, water content by Karl-Fischer titration (Crison Titromatic) according to ASTM E203-96, total acid number and pH (Mettler Toledo T50), density (Antor-Paar DMA35N)