



Rotary kiln and batch pyrolysis of waste tire to produce gasoline and diesel like fuels



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ABSTRACT

In this study, waste tire is pyrolyzed in a rotary kiln reactor to obtain more gas, light liquid, heavy liquid, wax products, and less carbon black at their maximum yields as, 20%, 12%, 25%, 8% and 35% of the total weight (4 tones), respectively. Then, the heavy and light oils are reacted with additives such as natural zeolite (NZ) and lime (CaO) at different mass ratio as 2, 6, and 10 wt%, respectively, in the batch reactor to produce liquids similar to standard petroleum fuels. The heavy and light oils mixture samples are distilled to observe their optimum graphics which are similar to gasoline and diesel like fuel. Consequently, the best results are obtained from the CaO sample with 10 wt% in comparison to the ones from the gasoline and diesel fuels. The 10 wt% CaO light liquid mixture resembles to gasoline named as gasoline like fuel (GLF) and the 10 wt% CaO heavy liquid mixture is similar to diesel called as diesel like fuel (DLF). The chemical and physical features of the waste tire, light oil, heavy oil, GLF, and DLF are analyzed by TG (thermogravimetric)/dTG (derivative thermogravimetric), proximate, ultimate, higher heating value (HHV), fourier transform-infrared spectroscopy (FT-IR), Brunauer–Emmett–Teller (BET), sulfur, density, viscosity, gas chromatography–mass spectroscopy (GC–MS), flash point, moisture, and distillation tests. The test results are turned out to be very close to the standard petroleum fuel.

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1. Introduction

Petroleum fuels have a negative effect on the environmental deterioration and cause health risks by using unlimited sources. The exhaust emissions have been reduced as an important development of the increasing the global protection and more strictive emission standards. Furthermore, the reliance of petroleum fuels is expected to decrease due to the limited resources [1]. The US energy division reported that the petroleum needs would extend to its highest output and consumption of the half of the output is expected at 2020 [2]. Alternative fuel production is already commercialized in the transportation sector along with the introduction of ethanol, methanol, biodiesel, LPG, CNG, waste material, etc. Among them, the waste materials such as tire, plastics and electronic have been suddenly increased in the environment and become the largest solid wastes in many countries. Thus, the waste material must be recycled to be used as fuel. For example, scrap tires have high potential as getting recycled at large tonnages and, also, getting collected without difficulty. For instance,

approximately, 150 million scrap tires were gathered in North America and 180 million in European Union countries [1].

The waste tires possess both a non-decomposed and non-biodegradable material. Thus, waste tires can cause terrible problems on the environment if they are not recycled properly. When the waste tires are disposed at dump sites, they can also cause serious human health, environmental and atmospheric problems. Besides, in such places waste tires keep destroying the ecology by bacteria growth, hosting mosquitoes, insects and pests through soil and groundwater [3]. Additionally, it causes high fire risk which cannot be easily extinguished and, also, the uncontrolled emissions of fire potential effect on the environment. The harmful compounds emitted from decomposing waste tire pollute the atmosphere, damage the ozone layer, absorb excessive sunlight and so on. As a solution, many scientific and budget programs have been developed about the specific legislations of waste tire [4,5].

In order to reduce the serious waste tire problems, many researchers have been studying converting the waste tire into a useful energy material in either gas, liquid or solid forms. Researchers and senior scientist have been working on various utilization techniques, such as pyrolysis [5–7], co-pyrolysis [8–10], incineration/combustion [11] and gasification [12]. However, all of these methods have noticeable drawbacks and limitations.

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Pyrolysis is an interesting method and, also, gets attention as a non-conventional technique in tire recycling research. In this process, the heat breaks down chemical bonds and decomposes the compound structure under non-oxygen atmosphere at high temperatures. Thereby, the high molecular weight polymers in tire rubber are reduced to low ones in forms of gas, solid and liquid that can be used as chemical energy resources. The inorganic residues such as steel and carbon black still remain solid at the end of this process [13].

The particle size used for the reaction was about 2 mm, and the reaction was conducted between 375 °C and 500 °C at a fixed bed reactor that was heated by 10 °C min⁻¹ heating rate, along with the protection of 100 mL min⁻¹ nitrogen gas flow rate for 1 h. The highest liquid yield (60 wt%) was obtained at 425 °C. The solid yield was decreased down to 26 wt% at 450 °C and then remained almost constant. The liquid fraction was observed to be at 79.77 wt %, and the liquids resemble to the standard fuel samples [14]. Banar et al. [15] has produced a tire derived fuel (TDF) at a temperature range between 350 °C and 600 °C, with 5 °C min⁻¹ and 35 °C min⁻¹ heating rates by raising 50 °C for each experiment at a batch reactor. At ended temperature 400 °C with heating rate 5 °C min⁻¹, the optimum oil yield is found to be 38.8 wt%. The chemical and physical property results of TDF are analyzed and found to be similar to the ones of diesel fuel. The higher heating value (HHV), viscosity, and sulfur content of the as-obtained liquid are found adequate to be burned as fuel. Islam et al. [13] studied on a small scale commercial tire plant that has been founded by Radiant Renewable Energy (RRE) Ltd. at Gazipur, Dhaka to reduce the liquid fuel crisis in Bangladesh. The plant has two pyrolysis units, each of which consists of a horizontal axis rotary type batch mode reactor (4.5 tons/run) that operates at 420 °C under 0.03 bar pressure. The oil, char, gaseous and steel cord product yields were 45 wt%, 35 wt%, 10 wt%, and 10 wt%, respectively at optimum reaction conditions. The liquid product's higher heating value (HHV) was about 44 MJ kg⁻¹, and this gives an idea that it can be used as an alternative instead of standard fuels. The gaseous product contains high amount of methane, ethane, butadiene and other hydrocarbon gases with an average HHV of approximately 37 MJ m⁻³, which was a significant value for their use as an energy source.

A continuous auger reactor with a nominal capacity of 150 kW_{th} (a pilot scale) was used to pyrolyze the waste tire. The reactor temperature was adjusted at 550 °C, under atmospheric pressure with nitrogen gas flow at 5 L_N min⁻¹ rate and a total mass flow rate of (6.7 ± 0.1 kg h⁻¹) for 3 min reaction time. The product yields were calculated as 40.5 ± 0.3 wt% (for the solid portion), 42.6 ± 0.1 wt% (for the liquid portion), and 16.9 ± 0.3 wt% (for the gas portion). The chemical and physical analyses of the as-produced samples were done and their results were compared with marine fuels based on the ISO 8217 standard. The gas and liquid products were determined to be useful for energy generation purposes [5]. Kwon et al. [16] investigated the CO₂-assisted mitigation of polycyclic aromatic hydrocarbons (PAHs) and (volatile organic carbons) VOCs in the waste tire pyrolysis by using a batch-type (laboratory-scale) reactor at 500 °C and 600 °C. The product C₁₋₅-hydrocarbons (HCs), (VOCs), and (PAHs) were qualitatively evaluated. In consequence, the co-pyrolysis of these products was considered as an environmentally benign and energy efficient process. Fernández et al. [7] investigated the separation fibers from rubber by pyrolysis process at 400 °C, 500 °C and 900 °C, with heating rate of 5 °C min⁻¹, in a horizontal oven. The as-obtained product properties (gas, oil and char) were analyzed.

The co-pyrolysis of scrap tire blends with ships waste oil to investigate the effect of waste oil on the scrap tire by producing a new alternative fuel. The experiments were conducted in a fixed bed reactor with and without a catalyst, at 500 °C. The catalyst

materials were either a commercial refined one or an industrial catalyst containing iron. The as-produced sample properties were analyzed and the analysis results gave the idea that the oil wastes had no effect on the scrap tire, but they improved its' fuel properties. The final co-pyrolysis oils were found to resemble the commercial diesel fuel (except their flash points and sulfur contents) and may be used as an environmentally friendly alternative for direct combustion in relevant engines [17]. Martínez et al. [8] studied on co-pyrolysis of forestry and tires waste which were pyrolyzed at a fixed bed reactor (the final pyrolysis temperature was 500 °C, at 80 °C min⁻¹ for 15 min residence time) and a continuous auger reactor (adjusted at final temperature of 500 °C, by using nitrogen gas which flowed at 5 L_N min⁻¹ and a mass flow rate was 5 kg h⁻¹, for 5 min reaction time). The waste tire and biomass were blended at different ratios, in order to upgrade the bio-oil quality. A radical interaction between the waste tire and biomass was occurred during the pyrolysis process. As experiment results, the waste tire was significantly reduced down to its aldehyde and phenolic compounds, which caused improvements in both the properties of bio-oil and its stability. The 90/10 (90% of biomass and 10% of waste tires) blend was found to be the highest liquid at the fixed bed reactor. Onay and Koca [9] tested the potential synergistic activities between the waste tire and lignite in a co-pyrolysis process. For the lignite-waste tire mixture tests, the final pyrolysis temperature, the heating rate and the reactor type were selected as 500 °C, 300 °C min⁻¹, well-swept fixed bed reactor (WSFB), respectively. The pyrolysis product characteristics were analyzed for each sample. The most remarkable blend ratio was determined to be the 10 wt % lignite to waste tire. Upon comparing the experimental and calculated results, it was indicated that the aromatic compounds' amount was increased while that of polar compounds' was decreased at the optimum conditions. As a result, the co-pyrolysis is determined to be an environmentally friendly technique for the conversion of hazardous waste into useful chemical materials. Acevedo and Barriocanal [10] recycled two types of waste, namely tire crumbs (TC) and fluff/fibers (RF), got them pyrolyzed and finally blended them with a low rank coal and a bituminous (BW) waste. The TC was blended with the coal at 1:1 ratio, as well as the RF/BW were mixed at 1:1 ratio in a fixed bed oven (6–8 g samples). The as-prepared blends were pyrolyzed at a quartz reactor with 5 °C min⁻¹ heating rate up to a final temperature of 850 °C. The final products' physico-chemical properties were analyzed. The aliphatic compounds in the final blends were increased along with the coal amounts in the mixture and also, the aromatics' amount was increased as a result of the co-pyrolysis process with bituminous. The co-pyrolysis of palm shells and scrap tires were optimized in a fixed-bed reactor under different temperature and ratios (100:0, 75:25, 50:50, 25:75, and 0:100) to improve both the quantity and quality of the liquid yields by adding scrap tire into the lignocellulosic biomass. At the first step of co-pyrolysis process, the optimum temperature was obtained at 500 °C for 60 min. Then, the temperature was increased up to 800 °C, about 45 min of pyrolysis time. The products (gas and liquid) yields were increased by the increasing temperature. The 50% biomass and 50% scrap tire was found to be the optimum ratio for improving the quality and quantity of products [18]. Zeaiter et al. [19] designed and manufactured an automated solar reactor system for catalytic pyrolysis of scrap rubber tires at 550 °C. The tire samples were exposed by H-beta and H-USY acidic catalysts, and also with a photoactive TiO₂ catalyst to compare their gas yields and composition after they were analyzed by GC-MS. The highest gas yield amount was obtained by H-beta catalyst (32.8%) while gasoline-like gas products obtained by TiO₂ (76.4%) and non-catalytic (88.4%) pyrolysis experiment results contained mainly isoprene. Based on the overall experimental results, the GC-MS analysis of hydrocarbons distributions were varied from C₁₀ to C₂₉ which indicated olefins and alkanes containing cyclic

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