EXPERIMENTAL FACTORS INFLUENCING PLASTICS PYROLYSIS WITH THE HORIZONTAL FIXED-BED REACTOR

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ABSTRACT

Plastic waste has emerged as a global environmental concern, with vast quantities of plastic materials being discarded and ending up in landfills or polluting natural ecosystems. Conventional waste management practices often fall short in effectively dealing with this mounting problem. As a result, alternative and sustainable solutions are being sought to address the challenges posed by plastic waste. One such solution gaining increasing attention is the waste plastic to oil extraction through the pyrolysis process. The objective of this study is to maximize the proportion liquid range product from pyrolysis of hydrocarbon plastics. In order to optimize the liquid range product, the effects of factors which influence the pyrolysis process need quantifying. Many of these factors affecting the distribution of the products have been already identified in various studies. However, some of the factors cannot be controlled in the process under the reaction conditions. Those adjustable factors will be controlled to optimize the process and to achieve the study objective.

Keywords: Plastic wastes, Plastic Pyrolysis, Experimental Factors, Horizontal Fixed-Bed Reactor.

1. INTRODUCTION

Pyrolysis is a chemical process that involves the decomposition of organic materials by heating them in the absence of oxygen. This thermal degradation leads to the breakdown of complex molecules into smaller fragments, such as gases, liquids, and char **[13].** Technology has gained significant attention as a promising solution for waste management and resource recovery. It involves the thermal decomposition of organic materials in the absence of oxygen, leading to the production of valuable products such as liquid oil, gas, and solid char **[5].** This process offers several advantages, including the ability to convert a wide range of feedstocks, including biomass, agricultural waste, and plastic, into useful end products. pyrolysis technology holds particular significance in the context of plastic waste management **[1].** With the increasing global plastic consumption and the subsequent rise in plastic waste generation, traditional waste management practices have proven inadequate in effectively addressing the problem **[9].** Pyrolysis presents an attractive alternative by enabling the conversion of non-recyclable and low-value plastic waste into valuable resources, such as pyrolysis oil or biofuel **[6].**

Theory of Pyrolysis Reactions:

The theory of pyrolysis reactions encompasses various mechanisms and pathways that occur during the process. Although pyrolysis is a complex phenomenon, two primary reaction types are commonly observed:

1. **Homolytic Pyrolysis:** In this type of pyrolysis, the organic material undergoes thermal decomposition through a series of radical reactions. The initial step involves the breaking of chemical bonds within the compound, resulting in the formation of highly reactive free radicals. These radicals can further react with other molecules, leading to a chain reaction. Homolytic pyrolysis is typically observed in the decomposition of hydrocarbons and other organic compounds with labile bonds.
2. **Heterolytic Pyrolysis:** This type of pyrolysis involves the cleavage of chemical bonds with the redistribution of electron pairs. Unlike homolytic pyrolysis, heterolytic pyrolysis involves the formation of charged intermediates or ions. Heterolytic pyrolysis reactions are commonly observed in the decomposition of more polar organic compounds, such as biomass and polymers.

The specific reaction pathways and products of pyrolysis depend on several factors, including the nature of the organic material, temperature, heating rate, and presence of catalysts or additives. During pyrolysis, various reaction mechanisms can occur simultaneously or sequentially, resulting in the formation of diverse products **[10]:**

1. **Gas-phase Reactions:** Pyrolysis produces a range of gaseous products, including hydrocarbons, carbon monoxide, carbon dioxide, methane, and other volatile organic compounds (VOCs). These gases can be utilized as fuels or further processed to obtain valuable chemicals.
2. **Liquid-phase Reactions:** The pyrolysis process also generates liquid products, such as bio-oils or pyrolysis oils. These oils are a complex mixture of oxygenated compounds, including aldehydes, ketones, acids, esters, and phenolic compounds. The composition and properties of the liquid products depend on the feedstock and pyrolysis conditions.
3. **Solid-phase Reactions:** The solid residue left behind after pyrolysis, known as char or biochar, consists primarily of carbonaceous materials. The char may contain some unreacted components, as well as carbonaceous structures with a high surface area. Char can be utilized as a soil amendment or activated to create activated carbon with adsorbent properties.

To optimize pyrolysis processes and understand the reaction mechanisms, researchers employ various techniques, including thermogravimetric analysis (TGA), gas chromatography-mass spectrometry (GC-MS), and Fourier transform infrared spectroscopy (FTIR) **[12].** These analytical tools help in characterizing the reaction kinetics, identifying intermediate species, and evaluating the pyrolysis products. Overall, the theory of pyrolysis reactions provides insights into the complex decomposition of organic materials and guides the development of pyrolysis technologies for biomass conversion, waste treatment, and production of renewable energy and chemicals **[2].**

The pyrolysis process involves three main stages: heating, pyrolysis, and condensation. During the heating stage, the waste material is heated to the desired temperature, typically within the range of 300 to 800 degrees Celsius. In the pyrolysis stage, the material undergoes thermal decomposition, resulting in the release of volatile compounds, including oil vapors and gases. The final stage, condensation, involves cooling the vapors and gases to obtain the desired end products, such as liquid oil and gas **[11].**

The key factors influencing the pyrolysis process include temperature, residence time, heating rate, and reactor design. Optimal control of these parameters is crucial to achieve higher yields of desired products and maintain process efficiency. Additionally, the use of catalysts, such as zeolites or metal oxides, can enhance the pyrolysis process by improving product quality and yield **[3].**

Pyrolysis technology offers numerous environmental benefits. By converting waste materials into valuable products, it reduces the reliance on fossil fuels and minimizes the need for landfill disposal. Furthermore, it has the potential to mitigate greenhouse gas emissions by displacing the use of conventional fuels with biofuels produced from pyrolysis oil **[1].**

Furthermore, pyrolysis technology presents a promising approach for waste management and resource recovery. It offers an efficient and environmentally friendly solution for converting various feedstocks, including plastic waste, into valuable products **[8].** Continued research and development efforts are essential to optimize the pyrolysis process, improve product quality, and enhance the economic viability of this technology. By harnessing the potential of pyrolysis, we can move towards a more sustainable and circular economy while addressing the challenges of waste management and reducing environmental impacts. This research paper aims to provide a comprehensive overview of the waste plastic to oil extraction process using pyrolysis. It explores the technical aspects of the pyrolysis process, including reactor design, temperature control, heating methods, and catalysts, to optimize the yield and quality of the obtained products. The paper also examines the composition and characteristics of different types of plastic waste and their impact on the pyrolysis process.

2. MATERIALS AND METHODS

In this work, a horizontal fixed-bed batch reactor was designed and constructed as shown in Figure 1. The goal for this experiment was to understand the process of the plastic pyrolysis by monitoring and analyzing the temperature profile. In the system, a M303PY Gallenkamp electronic furnace was applied to heat the reactor as an external heating resource. There are two heating sources in the furnace. The front one was used for heating the reactor in this experiment, which has a maximum power output of 881 W. The output power was dialed at Load 100 to provide its maximum power. The reactor was made of stainless steel pipe with an inner diameter of 28 mm and thickness of 2 mm. The system also consists of nitrogen purging bottle and a water-cooling condenser, both of which are connected to the reactor. Connected to the condenser are a liquid collector and a gas collector. The temperature on the outer wall of the reactor was measured by using thermocouples 1 (Thermal-well 1) and the centre space temperature in the reactor was measured using thermocouple 2 (Thermal-well 2). Thermal-well 2 is shown in Figure 1 (left).

The experiments used materials supplied by a plastic recycling company which was a mixer of 50% PE, 25% PP, and 25% PS (weight) in the form of post-consumer plastic chips. During the experiment, 10.00

grams of the supplied materials sample chips were placed in the centre section of a combustion boat inside the reactor that was for maintaining consistency of the sample location in the reactor. The combustion boat was half of a pipe that was separated into three sections. (Figure 1 right) The centre section was at the heating zone of the furnace, which had the highest temperature in the process.

After the test plastic chips were placed in the reactor, the system was sealed and the nitrogen gas was used as an inert gas to purge the whole system before the furnace started heating. This lasted about one minute. When the pyrolysis started and the plastics was heated and then decomposed once the temperature is high enough, the gases produced went through the water-cooling condenser and the temperature was reduced to about 30 ºC. Liquid and non-condensable gases were separately then collected separately. The process ended when no more products came out and the space temperature raised above 500 ºC. Non-condensable gas product was collected by a water sealed gas cylinder with which the volume of collected gases can be read during the reaction process. It was found that brown wax accumulated at the two ends in the combustion boat. The liquid products are yellow-brown oils.

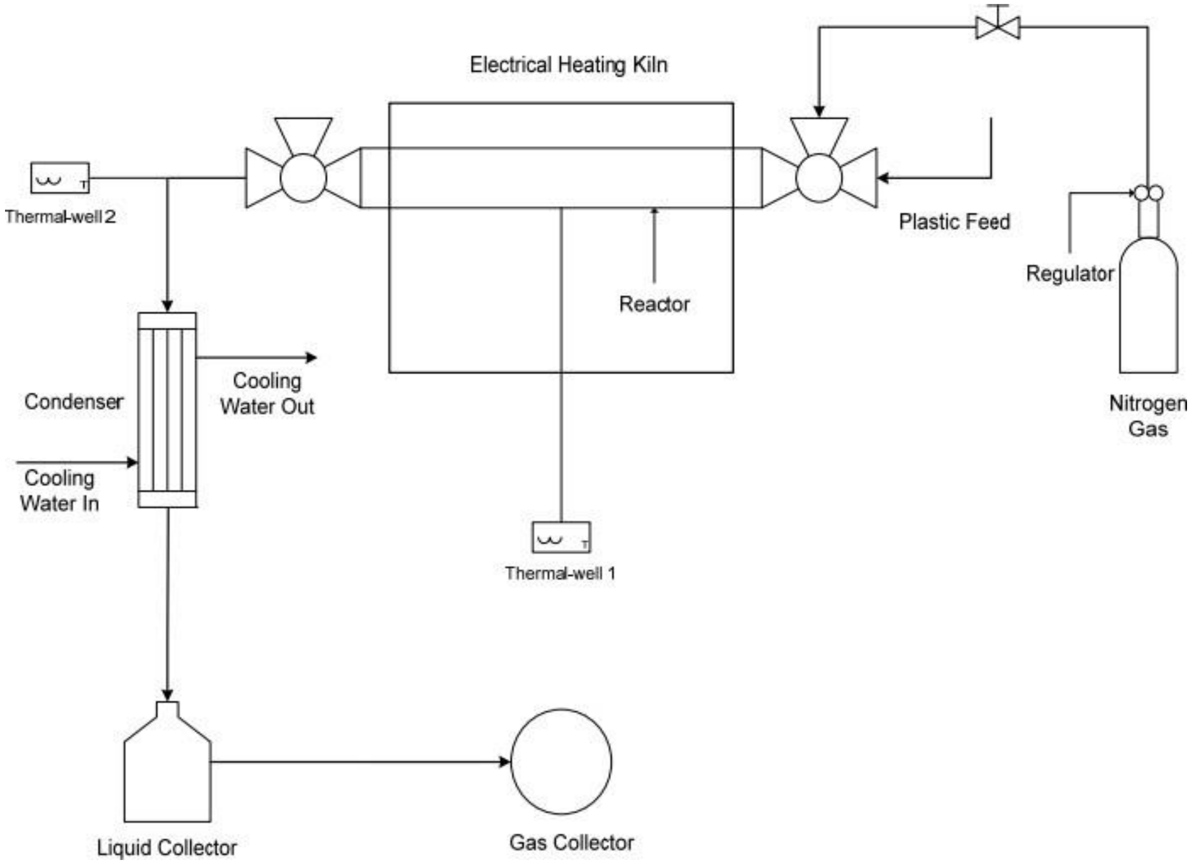

Fig. 1: Design of horizontal fixed-bed batch reactor

Fig.2: 1st Prototype (Experimental)

Table 1: Product distribution at different power output

Product (g)	Power Output Scale		
	100	80	60
Oil	2.08	3.5	4
Gas*	5.86	3.49	1.87
Gas Volume (L)	5.10	3.30	1.67
Char	1.22	1.28	1.3
Wax	0.84	1.73	2.83
Total	10	10	10

Note: *the mass of gas product is calculated from mass balances based on other collected products and the total mass of the feedstock

Effect of heating rate

"Heating rate" can be defined in many terms on various pyrolysis plants and researches. In a fast or flash pyrolysis, plastic will be cracked and vaporized very quickly once entering the pyrolysis reactor **[7].** In these cases, the heating rate hereby means the rate of temperature increasing per unit time during the contacting time, which can range from 100 up to 10000 K/s. On contrast, in a slow pyrolysis or a batch process, heating rate is normally from 10 to 100 K/s or less. However, in practice, the most convenient way to control the heating rate is to control the heating load to the pyrolysis reactor at given feeding rate

[4]. It has been found that heating rate has both effect on the pyrolysis reaction rate and the effect on the distribution of products.

The aims of this part of experimental studies were to experimentally examine the effect of heating rate on the pyrolysis process and the product distribution, and to identify how temperature triggered the cracking of the plastic mixture under the experimental conditions.

3. RESULTS AND DISCUSSION

The aims of this part of experimental studies were to experimentally examine the effect of heating rate on the pyrolysis process and the product distribution, and to identify how temperature triggered the cracking of the plastic mixture under the experimental conditions.

Product Yield and Composition: The waste plastic to oil extraction pyrolysis process demonstrated promising results in terms of product yield and composition. The primary products obtained from the pyrolysis of waste plastic were pyrolysis oil, gas, and solid residue (char). The composition of the pyrolysis oil varied, consisting of a mixture of hydrocarbons, including alkanes, alkenes, and aromatic compounds. The gas produced predominantly comprised carbon monoxide, carbon dioxide, methane, and other hydrocarbons. The solid residue or char contained carbonaceous material and ash.

Effect of Pyrolysis Conditions: The pyrolysis conditions, including temperature, residence time, and heating rate, significantly influenced the product yield and composition. Higher temperatures generally resulted in increased pyrolysis oil yield but with a higher proportion of light hydrocarbons. Lower temperatures favored the formation of heavy hydrocarbons. Optimizing the residence time helped achieve higher conversion rates and product yields, but prolonged residence times could lead to secondary reactions and undesired by-products. Controlling the heating rate was crucial to ensure efficient heat transfer and avoid thermal degradation of the feedstock.

Influence of Plastic Type: The type of plastic used as the feedstock had a significant impact on the pyrolysis process. Different plastics, such as polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET), exhibited variations in thermal properties, molecular structure, and decomposition behavior. As a result, the product yield and composition differed depending on the plastic type. For example, PE and PP plastics generally yielded higher amounts of liquid oil, while PS and PET plastics favored the formation of gases.

Catalytic Pyrolysis: The use of catalysts in the pyrolysis process showed promising results in terms of improving product quality and increasing the yield of desired products. Catalysts, such as zeolites, metal oxides, or activated carbon, were found to enhance the cracking of hydrocarbons, reduce coke formation, and suppress undesirable reactions. Catalytic pyrolysis led to higher yields of liquid oil with improved properties, such as lower viscosity and higher calorific value.

Environmental Implications: The waste plastic to oil extraction pyrolysis process demonstrated potential environmental benefits. By converting waste plastic into valuable products, it contributed to waste reduction, mitigated landfill usage, and reduced environmental pollution. Moreover, the produced pyrolysis oil had the potential to be used as a substitute for conventional fossil fuels, thereby reducing greenhouse gas emissions and dependence on finite resources.

Challenges and Future Directions: Several challenges and areas for improvement were identified during the research. The optimization of pyrolysis conditions to achieve higher yields and better product quality remains a focus area. Further investigation is required to develop more efficient and selective catalysts for enhanced catalytic pyrolysis. Additionally, the utilization of by-products such as char and gas needs to be explored to maximize the resource recovery potential of the process. Further research and development are necessary to optimize the process parameters, scale-up the technology, and address any environmental concerns associated with the pyrolysis process.

4. CONCLUSION

The waste plastic to oil extraction pyrolysis process demonstrated promising results in terms of product yield and composition. The pyrolysis conditions, plastic type, and use of catalysts significantly influenced the process outcomes. The process has potential environmental benefits, such as waste reduction and resource recovery, while also contributing to renewable energy generation. Furthermore, the environmental implications of waste plastic pyrolysis are addressed, including the management of emissions, by-products, and waste residues. The economic viability and commercial potential of waste plastic to oil extraction are explored, considering factors such as operational costs, market demand, and regulatory frameworks. By delving into the technical, environmental, and economic aspects, this research paper contribute to the understanding and development of waste plastic to oil extraction through pyrolysis. The findings and insights presented will inform stakeholders, policymakers, and researchers in advancing this technology and promoting its adoption as a sustainable solution for plastic waste management.

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