Waste Plastic Pyrolysis: Transforming Plastic Waste into Hydrocarbon Fuels Dr. SAMUDRALA PRASANTHA KUMARI

Abstract - Plastics have become an essential part of modern society, yet their waste accumulation poses significant environmental challenges. pyrolysis, a thermochemical process, provides a sustainable solution by converting plastic waste into valuable hydrocarbon fuels. This study explores the process of plastic pyrolysis, factors influencing fuel yield, reactor designs, and kinetic mechanisms. The investigation aims to optimize pyrolysis conditions and develop a semicommercial continuous pyrolysis apparatus for effective waste-to-energy conversion.

I. INTRODUCTION

1.1 Background

Plastics, first invented in 1862 by Alexander Parkes, are highmolecular-weight polymers extensively used across industries. The Society of the Plastics Industry (SPI) classifies plastics into seven types. Global plastic production has significantly increased, from 1.5 million tons in 1950 to 260 million tons in 2007, creating substantial waste management challenges. For instance, in 2007, the U.S. generated 30.7 million tons of plastic waste, while Europe consumed approximately 60 million tons annually.

New Zealand imported 262,904 tonnes of virgin plastics in 2004, yet only 13.5% of post-consumer plastics were recycled. Due to the durability of plastics, the majority end up in landfills, remaining for decades. With increasing plastic consumption and limited landfill space, alternative solutions such as biodegradable plastics and advanced recycling technologies are being explored. Pyrolysis offers a viable method to convert plastic waste into fuel, addressing both environmental concerns and energy shortages.

1.2 Economic Value

Plastic pyrolysis not only conserves land resources but also provides an alternative energy source. Christchurch alone generated 243,054 tons of municipal waste in 2003–2004, with plastics accounting for 15%. Converting this plastic waste into fuel could reduce reliance on fossil fuel imports. Moreover, pyrolysis-derived fuels are sulfur-free, preventing air pollution from sulfur dioxide emissions.

1.3 Pyrolysis of Plastic Materials

Pyrolysis is a thermal decomposition process in an oxygenfree environment that breaks plastics into smaller hydrocarbons. Unlike landfilling or incineration, pyrolysis reduces waste accumulation and prevents toxic emissions. HDPE, LDPE, PP, and PS are particularly suitable due to their high calorific values, comparable to traditional fuels like LPG and diesel. Some commercial pyrolysis plants utilize catalysts to improve fuel quality, although challenges remain, such as optimizing material resistance time and heat transfer efficiency.

II. OBJECTIVES OF THE INVESTIGATION

This study aimed to optimize the pyrolysis process to maximize oil yield and design a semi-commercial continuous pyrolysis apparatus. The focus was on HDPE, LDPE, PP, and PS, which constitute 70% of packaging plastics. PVC and PET were excluded due to hazardous emissions.

The study was conducted in three stages:

- 1. **Understanding Thermal Cracking** Identifying key factors affecting pyrolysis and product quality, such as reaction temperature, secondary cracking, heating rate, plastic type, catalysts, and plastic interactions.
- 2. **Optimizing Process and Reactor Design** Improving operational conditions to produce high-quality diesel from LDPE and analyzing products using gas chromatography (GC) and mass spectrometry (MS).
- 3. **Developing a Continuous Pyrolysis Apparatus** Constructing a reactor to convert LDPE and PE-PP-PS mixtures into gas and liquid fuels, with a system comprising a feeding section, pyrolysis reactor, and separation unit.

III. LITERATURE REVIEW ON PLASTIC PYROLYSIS

3.1 Factors Affecting Pyrolysis

3.1.1 Feedstock Composition

The efficiency and product distribution in pyrolysis depend on the chemical structure of plastics. PE, PP, and PS were selected due to their common hydrocarbon composition. Polymer classification (linear, branched, or cross-linked) also influences thermal degradation behavior. For example, PS yields high amounts of styrene due to side-group detachment.

3.1.2 Cracking Temperature and Heating Rate

Temperature is critical in polymer breakdown, as decomposition occurs when thermal energy exceeds C–C bond enthalpy. Higher temperatures typically increase gas yield while decreasing liquid output. Heating rate also impacts reaction dynamics; rapid heating rates promote fast pyrolysis, yielding more liquid hydrocarbons.

3.1.3 Reactor Types

The reactor type influences heat transfer, mixing, residence time, and reflux. Reactors are classified as batch, semi-batch, or continuous:

- **Batch:** Feedstock is loaded at the start, and products are removed after completion.
- **Semi-Batch:** Products are continuously removed while feedstock is initially added.
- **Continuous:** Feedstock is continuously fed, and products are removed simultaneously.

Further classification is based on reactor bed types:

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- **Fixed Bed:** Simple design but sensitive to feedstock shape irregularities.
- Fluidized Bed: Ensures uniform temperature and high heat transfer but requires separation of bed material from gases.
- Screw Kiln: Uses an extruder for stable processing and controlled residence time.

3.1.4 Residence Time

- Residence time impacts product yield:
- Fast Pyrolysis: Short residence times favor liquid yield.
- **Slow Pyrolysis:** Longer residence times promote tar and char formation.

Adjustments in feed rate, gas flow, and discharge rate help optimize residence time for desired product distribution.

3.1.5 Catalyst Use

Catalysts enhance fuel quality by reducing molecular weight and increasing stability.

- Homogeneous Catalysts: Lewis acids (e.g., AlCl3).
- Heterogeneous Catalysts: Zeolites, clays, and metalsupported catalysts. Zeolites (e.g., ZSM-5) are preferred due to thermal stability and efficiency.

3.1.6 Pressure Influence

Higher pressure raises the boiling point, promoting further cracking of heavy hydrocarbons, leading to increased gas yield and reduced liquid yield.

IV. ANALYSIS OF PLASTIC PYROLYSIS REACTION KINETICS AND ENERGIES

4.1 Pyrolysis Reaction Mechanisms

4.1.1 Chain Cracking Mechanisms

- Random Cracking: Common in PE, PP, and PS.
- Chain Strip Cracking: Side groups detach first.
- End Chain Cracking: Degradation starts from chain ends, yielding smaller hydrocarbons.

4.1.2 Reaction Stages

- 1. Initiation: Polymer chains break into free radicals.
- 2. **Propagation:** Further breakdown via β-scission.
- 3. **Hydrogen Transfer:** Reduces polymer molecular weight.
- 4. **Termination:** Finalizes the reaction by forming stable hydrocarbons.

4.2 Kinetics of Plastic Pyrolysis

Reaction rates are influenced by catalysts, reactor types, and plastic composition. The Arrhenius equation governs reaction kinetics: where is activation energy, is the pre-exponential factor, is the gas constant, and is temperature.

Energy demand calculations confirm that polyethylene (PE) pyrolysis is endothermic, requiring heat input. The total energy required for pyrolyzing 1 kg of PE is approximately 1047.62 kJ, with a net energy gain of ~42.3 MJ/kg, aligning with literature values (~41.7 MJ/kg).

V. CONCLUSION

Plastic pyrolysis presents a viable waste management and energy recovery solution. The process consists of initiation, propagation, hydrogen transfer, and termination stages, with key cracking mechanisms (random, end-chain, chain-strip) influencing product composition. Understanding these mechanisms enhances pyrolysis efficiency and fuel quality. Further research and optimization will facilitate commercial implementation and environmental sustainability.

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