Analysis and comparison of Thermal and Electrified Pyrolysis for Plastic Waste Valorization: A Pathway Towards Circular Economy and Low-Carbon Fuels

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Abstract

The transition to a circular economy and low-carbon energy generation necessitates new waste valorization technologies. Pyrolysis of plastic waste to produce high-value chemicals and fuels is one such new potential solution. In this paper, a comprehensive numerical modeling of a pyrolysis-based waste-to-fuel (WTF) process is presented, designed using Aspen Plus®, with a focus on process simulation, sensitivity analysis, product upgrading, and techno-economic analysis. The simulation was established by setting up an optimal flow diagram involving pretreatment, pyrolysis, and upgrading of reaction products thereafter. The model considers the heterogeneous character of Plasmix, integrating thermodynamics and kinetics to determine product yields and compositions. Principal products are char, tar, and syngas, whose yields are determined by operating conditions.

Sensitivity analysis indicates that temperature has a strong impact on the product distribution, with an optimal temperature range of 600-750°C giving the highest pyrolysis oil yield. Increasing temperature promotes gas production, and higher pressures drive the equilibrium towards heavier hydrocarbons. The results of modeling were compared with experimental data and found to show excellent agreement in both product composition and overall system performance. Comparative performance of thermal and electrified pyrolysis was investigated to assess their environmental and economic efficiency. Electrified pyrolysis with the use of renewable electricity as the heat source reduces the greenhouse gas emissions and increases energy efficiency. The sustainability of the process was also determined through an energy balance, carbon footprint calculation, and legislative compliance with Low Carbon Fuels (LCF) directive. Product upgrading mechanisms were explored to enhance fuel quality. The syngas stream underwent a water-gas shift (WGS) reaction for hydrogen enrichment to allow hydroprocessing. Pyrolysis oil, which is aromatic hydrocarbon rich, underwent hydrocracking on bifunctional catalysts (Pt-Pd/HZSM-5) to produce Sustainable Aviation Fuel (SAF) and other premium fuels. Tar conversion kinetic modeling was included in the simulation, adjusting reaction conditions for optimum hydrocarbon yield at minimum coke generation and catalyst deactivation.

A techno-economic analysis (TEA) was undertaken, considering operational and capital expenses (OpEx and CapEx), available revenue from the sale of fuel, and policy support. The financial feasibility of the process was established to be comparable with conventional fossil fuels. Market trends and investment opportunities for recycled carbon fuels (RCF) were also discussed, referring to regulatory regimes like the ReFuelEU Aviation action plan. In conclusion, the study highlights the promise of pyrolysis as a green solution to waste-derived fuel generation. Coupling computational simulation with experimental proof-of-concept and economic viability analysis, the research provides a solid foundation for innovation in waste-to-fuel technology. The findings urge greater research and development of electrified pyrolysis and catalyst optimization to enable greater efficiency and scale-up for improved support towards world decarbonization and circular economies.

Keywords: *Pyrolysis, Plastic Waste, Circular Economy, Simulation, Tecno-economic Analysis*