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Title

Turning Tyre Waste into Energy: Sustainable Valorisation via Microwave-Induced Plasma Gasification

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Abstract

Introduction

The United Nations has emphasised the urgent need to transition towards a more sustainable and resource-efficient global economy, with improved waste management identified as a key enabler. One major challenge is the disposal and valorisation of end-of-life tyres. The global tyre industry produces approximately 3.66 billion tyres annually, creating significant environmental and energy concerns. Conventional disposal routes, such as landfilling and incineration, are associated with toxic emissions, environmental risks, and poor energy recovery. In this context, gasification offers a promising route for converting waste into valuable energy carriers.

This paper investigates microwave-induced plasma gasification as a sustainable alternative for tyre waste treatment. Experimental studies are conducted using a novel microwave plasma furnace equipped with a mode converter that maintains the plasma core away from reactor walls, improving thermal efficiency and eliminating the need for ceramic linings. Tyre crumb is used as a representative feedstock. Although tyres are generally safe to handle, their combustion can release 10-100 times more polycyclic aromatic hydrocarbons than coal, whereas gasification enables cleaner conversion into synthesis gas.

Microwave plasma gasification achieves efficient destruction of complex organics, producing inert ash with negligible fixed carbon and significantly reduced VOC emissions. Independent control of temperature and oxidant supply enables optimisation of syngas quality and process economics. Ongoing research at Lancaster University focuses on improving applicator efficiency and advancing scalable, energy-efficient waste-to-energy technologies.

Methods

Previous gasification research at Lancaster University employed a 2.45 GHz, 6 kW microwave-induced plasma torch (Sairem SAS, France). Atmospheric-pressure microwave plasmas are most readily sustained within electrically insulating, microwave-transparent ceramic vessels, which reduce electron losses and enable operation at lower power. In this system, the plasma torch comprised a fused silica tube (25.4 mm internal diameter) passing through a WR340 rectangular waveguide operating in the TE_{10} mode. Microwave leakage was suppressed using concentric metallic chokes, while plasma ignition was achieved via a transient tungsten arc. Although effective, the fused silica tube required intensive cooling to prevent thermal damage, significantly reducing system efficiency.

To address these limitations, a new applicator was developed to increase plasma volume, enable scale-up, and eliminate the need for a cooled ceramic tube. The design operates in the TE_{01} mode of a cylindrical waveguide, where the azimuthal electric field and low wall field strength minimise electron and heat losses, improving thermal efficiency. For 2.45 GHz operation, a cylindrical diameter of 182 mm was selected and a dedicated mode converter fabricated. While stable operation requires specific gas flow and power thresholds, the design is readily scalable to 915 MHz, where magnetron efficiencies exceed 90%, enabling industrial-scale processing. Independent control of gas flow and power can be achieved through hot-gas recirculation, further optimising gasification performance.

Results

The current test bed comprises three main components: a microwave plasma chamber, a gasification furnace, and a gas recirculation system. The gasification stage of the process is modelled using ASPEN Plus, enabling heat and enthalpy balancing under assumed constant pressure and enthalpy conditions. Although the overall system operates as a single reactor experimentally, a hybrid modelling approach is adopted, dividing the gasification process into three stages: drying at 105 °C, pyrolysis at 500 °C (modelled using an RYield block), and gasification (modelled using an RGibbs block). Heat for drying and pyrolysis is supplied by the plasma exhaust stream, while the final gasifier temperature depends on reaction heat and available exhaust energy. Two operating cases are examined: without syngas recirculation and with recirculation. In the non-recirculation case, air is heated by microwave input in the plasma chamber and fully directed to the gasifier. In the recirculation case, the plasma is modelled using three temperature zones to reflect realistic plasma–gas interactions, followed by heat exchange and partial syngas extraction. ASPEN Plus simulations indicate that an optimal airflow of 16.5 kmol h^{-1} eliminates fixed carbon while minimising undesirable by-products. Importantly, incorporating up to 80% gas recirculation significantly reduces exhaust temperatures and microwave power demand by a factor of approximately 2.8 without adversely affecting syngas composition or calorific value, thereby improving overall process efficiency and economics.

Conclusions

A stable atmospheric-pressure microwave-induced plasma was successfully generated within a steel vessel, demonstrating robust and controllable operation. The high-temperature plasma exhaust exhibited the thermal intensity and chemical reactivity required to effectively gasify a range of waste feedstocks, including tyre crumb. Key operational parameters governing efficient plasma formation and stability were identified, providing essential baseline data for the

evaluation of tyre-derived materials as viable feedstocks in plasma-assisted gasification processes.

These results highlight the strong potential of microwave-induced plasma technology as a cleaner and more efficient alternative to conventional thermal treatment methods, offering enhanced destruction of organic compounds with the prospect of reduced harmful emissions. Importantly, stable operation at atmospheric pressure significantly improves the practicality of this approach, supporting the development of compact and modular waste-to-energy systems. Such systems could be deployed closer to waste generation sites, thereby reducing transportation requirements, lowering environmental impact, and advancing sustainable waste management strategies.

Keywords

Microwave plasma; Advanced gasification; Sustainable valorisation; Tyre crumb; Process modelling.

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