

Plasma-based process concept with CO₂ capture for the utilization of complex and hazardous waste: A circular economy approach

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Keywords: solid hazardous waste, plasma-assisted thermal treatment, circular design framework
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Introduction

For many complex and partially hazardous waste streams, existing recycling and thermal treatment methods fail to provide sustainable solutions that effectively close material cycles. Such waste streams are typically characterized as problematic, mainly due to their composite nature, resistance to thermal degradation and the high risk of toxic substances during disposal or treatment.(1) Typical examples of such waste streams include carbon and glass-fiber reinforced polymers, electronic circuit boards, waste from the chemical and construction industry, rubber-containing waste, tar-containing materials, and other hazardous residues, which represent a growing portion of global waste.(3) To address this issue, this paper proposes a novel waste management framework integrating plasma-assisted thermal treatment with CO₂ capture, providing a comprehensive and innovative system for managing hazardous waste while addressing carbon emissions.

Method

The conceptual design in this paper focuses on combining advanced thermal treatment with CO₂ capture to maximize resource recovery and minimize environmental impact. To break down complex waste into useful byproducts like syngas, inert slag, and recovered metals, plasma systems leverage higher than conventional processes temperatures in controlled environments. (2) The creative method presented here offers a cutting-edge substitute for conventional combustion systems, greatly lowering harmful emissions while improving material repurpose and energy recovery. The combination of plasma technology and CO₂ capture forms a holistic waste management system for hazardous waste that aligns with circular economy principles in terms of energy and material recovery and repurpose. This integrated approach represents a significant advancement over traditional combustion systems, addressing both environmental challenges of complex waste disposal and the urgency of climate change mitigation.

Target waste streams are identified in this paper based on their current applicable treatment method, hazardous level, structure and complexity, as well as potential for energy and material recovery. While the system is designed to handle a broad range of complex and hazardous waste, mainly due to the flexibility of plasma thermal systems, the identified waste of interest poses already significant challenges for conventional waste management practices, due to their characteristics, like high thermal stability, potential of toxic substances release and complex structure. The system is designed to process such feedstocks without requiring significant pre-treatment, ensuring adaptability to industrial waste streams that are heterogeneous and difficult to recycle.

Static balance models are applied to examine mass and energy flow in the system's main parts, including the combustion chamber, cooling system, and CO₂ capture unit. This analysis also identified the electrical and thermal capabilities of the components (including the plasma system) needed for efficient operation under various conditions, ensuring the system's effectiveness and practical application. The insights gained from these models help determine processing limits and performance benchmarks, setting the stage for incorporating plasma technology as an efficient method for complex and hazardous waste thermal treatment. The main goal of the system design is to enable the plasma thermal treatment of various hazardous waste streams, making it a flexible and scalable solution for industries dealing with complex waste challenges.

Results and Discussion

The modeling results validate the feasibility and flexibility of the proposed system in handling diverse hazardous and complex waste streams. The energy and mass flow analysis provided critical insights into the operational capacity of key components, including the combustion chamber, cooling system, and CO₂ capture unit. Insights into the energy demands, as well as byproduct utilization have also been identified through the analysis. The models also determined the required electrical and thermal inputs to optimize process efficiency under various operational scenarios. The findings highlight the system's ability to process heterogeneous waste offering adaptability to a wide range of industrial applications. Furthermore, the production of byproducts such as syngas, inert slag, and recoverable metals demonstrates the potential for resource recovery and alignment with circular economy objectives, providing a concept of “Waste-to-Product”. These results provide a robust foundation for the system’s conceptual design, ensuring its scalability and alignment with industrial requirements for managing hazardous waste streams efficiently.

This innovative concept is designed and integrated as part of a circular economy approaching, transforming waste management into a resource recovery system. By prioritizing energy recovery, material repurpose and efficient solution for complex and hazardous waste, the proposed system offers a closed-loop solution that aligns with global sustainability goals, while addressing a relatively unexplored area of hazardous waste treatment. This operational framework demonstrates the potential but also the feasibility of hazardous waste to be integrated into industrial value chains as secondary raw materials, reducing environmental impact and supporting resource efficiency.

Conclusion

To conclude, this paper outlines the conceptual design, static modeling results, and integration of plasma technology and CO₂ capture technology into a broader sustainable thermal waste treatment system. The proposed system represents a significant step forward in addressing the inefficiencies of traditional methods, combining technological innovation with environmental responsibility to create a scalable and future-ready solution for managing hazardous waste streams.

References

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