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Transforming Waste into a Valuable Resource: Plasma Technology as a Clean Energy Source

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***Abstract*— In an era of rapid urbanization and industrial expansion, this paper addresses the pressing issue of overpopulation and its direct consequence: environmental contamination. To tackle this challenge, a sustainable and environmentally friendly approach is crucial, particularly in managing the excessive waste generated. One promising solution meeting these criteria is plasma technology for waste treatment. This article divides the discussion into four main sections: the problem of waste generation and its consequences; an introduction to plasma technology for waste treatment; a detailed system operation and energy generation from obtained products; and an analysis of advantages, potential limitations, and overall performance. In sum, this article promotes the adoption and improvement of plasma waste treatment technology to reduce waste, generate clean energy, and foster a healthier environment in the face of urbanization and industrialization challenges.**

Keywords: **plasma technology – gasification - syn gas - sustainable energy**

***Resumen*— En una época de rápida urbanización y expansión industrial, este artículo aborda el crítico problema de la superpoblación y su consecuencia directa: la contaminación ambiental. Para enfrentar este desafío, es fundamental un enfoque sostenible y respetuoso con el medio ambiente, especialmente en la gestión de los excesivos residuos generados. Una solución prometedora que cumple con estos criterios es la tecnología de plasma para el tratamiento de residuos. Este artículo divide la discusión en cuatro secciones principales: el problema de la generación de residuos y sus consecuencias; una introducción a la tecnología de plasma para el tratamiento de residuos; una explicación detallada del funcionamiento del sistema y la generación de energía a partir de los productos obtenidos; y un análisis de ventajas, posibles limitaciones y desempeño general. Finalmente, este artículo promueve la adopción y mejora de la tecnología de tratamiento de residuos con plasma como un medio para reducir los residuos, generar energía limpia y fomentar un entorno más saludable ante los desafíos de la urbanización y la expansión industrial.**

Palabras clave: **tecnología plasma – gasificación – gas sintético - energía sustentable**

I. Introduction

Over the last centuries, cities, along with industrialization, have expanded exponentially, reaching almost every corner of the world. The direct consequence of this is clear: overpopulation. In this context Within such large number of people with little to no awareness of sustainable ways of life, leads to a problem which directly affects everyone: environmental contamination.

An environment with large amounts of pollution is uninhabitable, so urbanization and industrial processes` residues ought to be treated. The United Nations (UN) establishes in its 2030 Agenda the proper ways to achieve it, by means of its Sustainable Development Goal (SDG) Nº 9, “Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation” [1, p.39]. It is also indirectly related to other SDGs, such as Nº6, “Ensure availability and sustainable management of water and sanitation for all” [1, p. 27]; Nº8, “Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all”; and Nº 11, “Make cities and human settlements inclusive, safe, resilient and sustainable” [1, p. 32].

In order to address this issue, it is important to acquire the knowledge and practices necessary to efficiently manage a large amount of waste, so as to obtain benefits such as energy generation using organic matter. Therefore, in pursuance of the stated goals, a sustainable and environmentally friendly approach has to be used.

One of the methods or processes that meets the above conditions is waste treatment using plasma technology, which is a promising and efficient alternative. However, the challenges include the initial cost and the precise technical design. Despite this, plasma waste treatment presents a viable and attractive approach to waste management.

In this article, the topic of waste treatment using plasma technology to generate clean energy will be addressed by dividing it into four main sections. First, the problem of waste generation and its consequences will be presented. Secondly, a definition of plasma technology applied to waste treatment will be provided. After that, the system’s operation will be explained in detail, describing the components and relevant operational aspects, followed by an elucidation on how the obtained products can be used for energy generation. Finally, an analysis will be carried out that will consider the advantages, the possible limitations, and the general performance of this technology. It is expected that this work will contribute to the dissemination of the described technology, which results in its widespread usage and improvement, impacting directly on waste reduction and clean energy generation, leading to a healthier environment.

II. OVERCONSUMPTION AND OVERPOPULATION

As urbanization continues to expand, cities and metropolitan areas around the world are facing significant challenges in dealing with the growing issue of municipal solid waste (MSW). If this waste is not collected and managed in a responsible manner, it can act as a breeding ground for infections, contribute to plastic pollution and release greenhouse gas emissions [2, p. 49].

The anticipated global annual waste generation is forecasted to experience a substantial surge to 3.4 billion tonnes within the next 30 years, marking a notable increase from the recorded 2.01 billion tonnes in 2016. Collectively, high-income nations account for over a third (34%) of the total global waste generated. On the other hand, the East Asia and Pacific region is responsible for producing nearly a quarter (23%) of the world's waste [3, p. 2].

As it can be seen in [2, Fig. 1], in 2022, globally, around 82% of MSW was collected, with 55% being managed in controlled facilities. Sub-Saharan Africa and Oceania have an average collection rate below 60%. In Asia, Latin America and the Caribbean, cities have relatively higher collection rates, ranging from 70% to 85%. Central and Southern Asia face a larger gap between collection and controlled management rates, indicating a reliance on open dumpsites. Adequate investment, improved policies, and strengthened environmental law enforcement are necessary for effective waste management, particularly in low to middle-income countries [2, p. 49].

Fig. 1. Percentage of MSW collection and management in controlled facilities in 2022 [2]

III. PLASMA TECHNOLOGIES: AN INNOVATIVE METHOD FOR WASTE MANAGEMENT

An unconventional and little-known method that can be used for solid waste reduction is one that uses “plasma technology”. This cutting-edge process is innovative as well as highly efficient in material transformation.

A. Introduction to plasma

Plasma is a distinct state of matter, often referred to as the "fourth state", apart from the more commonly known solid, liquid, and gas ones. To reach this state, a gas is heated to extremely high temperatures or subjected to intense energy, causing a significant number of its atoms to lose one or more electrons. This process is called “ionization”, and it transforms it into an ionized gas or plasma, wherein a mixture of positively charged ions and free electrons coexists [4, p.309].

One of the most remarkable features of plasma is its ability to conduct electricity. Unlike the occurrence in normal gases, with electrically neutral atoms due to an equal number of protons and electrons, plasmas contain free electrons that can move freely, enabling the flow of electrical current. This property makes it essential in various technological applications, such as in plasma televisions, fluorescent lights, and fusion reactors [5, p. 4].

Another striking aspect of plasma is its response to electromagnetic fields. The presence of charged particles means it can be influenced and manipulated by magnetic and electric fields. This property is used in its confinement for controlled nuclear fusion experiments [5, p. 4].

A simple description of the gas treatment is given by Anyaegbunam:

> Artificial Plasma may be created by passing a process gas, which serves as a dielectric, between objects with large electrical potential differences. The potential difference and subsequent electric field cause ionization of the gas and electrons are pulled toward the anode while the nucleus pulled towards cathode. […] The presence of this ionized gas allows the formation of an electric arc between the two electrodes, and the arc serves as a resistive heating element with the electric current creating heat which creates additional plasma that allows the arc to be sustained. […] Interaction between the arc and process gas introduced into the torch causes the temperature of the gas to be very high and the hot gas can exit the plasma torch at about 10,000°C [5, p. 4].

The plasma torch´s operation can be seen in [5, Fig. 2]. This visual depiction not only shows the dynamic interplay within the torch's core but also offers a glimpse into the thermal transformation that occurs as electric currents amalgamate with the process gas, resulting in temperatures higher than average.

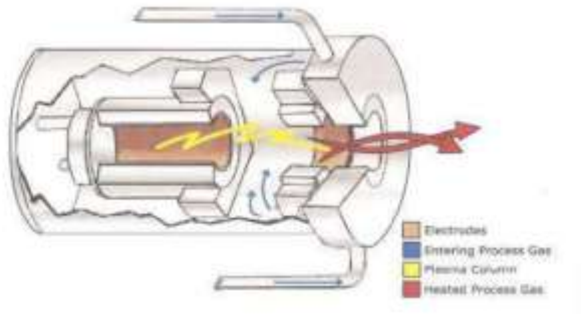

Fig. 2. Plasma Torch [5]

B. Gasification and Chemical Reactions

Gasification is a thermochemical process that involves the conversion of carbon-containing feedstocks, such as MSW, coal, petroleum coke, or biomass, into a syngas, also known as synthesis gas. The syngas primarily consists of carbon monoxide (CO) and hydrogen (H2). This conversion process occurs under controlled conditions, typically at elevated temperatures and/or pressures, and with the presence of controlled amounts of oxygen, which can be supplied by air, oxygen-enriched air (essentially pure oxygen), or steam [5, p. 6].

The detailed main reactions are [5, eq. (1)-(5)]:

$CH_4 + H_2O \rightarrow CO + 3H_2$ (CH_4 decomposition-endothermic) (1)

$CO + H_2O \rightarrow CO_2 + H_2$ (water gas shift reaction-exothermic) (2)

$C + H_2O \rightarrow CO + H_2$ (Heterogeneous water gas shift reaction-endothermic) (3)

$C+CO_2 \rightarrow 2CO$ (Boudouard equilibrium-endothermic) (4)

$2C + O_2 \rightarrow CO$ (5)

The global gasification reaction is [5, eq. (6)]:

$$CHxOy + wH_2O + mO_2 + 3{,}76mN_2 \rightarrow aH_2 + bCO + cCO_2 + dH_2O + eCH_4 + fN_2 + gC \quad (6)$$

Where w is the amount of water per mole of waste material, m is the amount of O_2 per mole of waste, a, b, c, d, e, f and g are the moles of the gaseous products. The concentrations of individual gases are determined based on the quantities of injected O_2, H_2O and the input thermal plasma enthalpy.

C. System´s Operation

Plasma gasification is an advanced and environmentally responsible thermal waste treatment method that occurs in an oxygen-starved environment to promote gasification rather than incineration of waste materials. The process involves the utilization of plasma heat within a vertical shaft cupola, which draws inspiration from the foundry industry. Westinghouse Plasma Corporation (WPC) has developed a plasma gasification system based on this concept.

The plasma gasification process is depicted in [5, Fig. 3]. At the core of the system lies the plasma gasifier, a vertical vessel lined with refractory materials, where the waste feed material is introduced near the top, along with metallurgical coke and limestone. Positioned near the bottom of the vessel, plasma torches direct high-temperature process gas into a bed of coke. Simultaneously, air or oxygen is introduced through nozzles located above the torches.

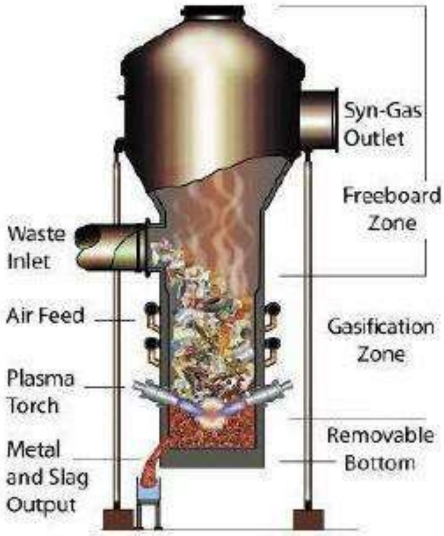

Fig. 3. Plasma gasification process broken down [5]

The plasma torches raise the temperature of the coke bed to an extremely high level, creating a heat reservoir, while the process gas moves upward through the gasifier vessel, causing the gasification of the waste materials. The powerful capabilities of plasma gasification render it an environmentally clean technique for waste treatment.

In the gasification process, additional heat is generated by the reaction between the carbon present in the waste and the oxygen introduced through the nozzles. This reaction produces carbon monoxide. The resulting hot product gas then ascends through the waste, breaking down organic compounds and drying the waste located at the upper part of the gasifier.

Simultaneously, as the waste progresses downward through the gasifier vessel, inorganic materials like metal, glass, and soil are subjected to high temperatures, causing them to melt. Consequently, a two-phase liquid stream is formed, comprising molten metals and a glass-like (vitrified) residue. This liquid stream flows towards the bottom of the vessel. Upon discharging the molten material into water, a transformation occurs, leading to the formation of metal nodules and a coarse sand-like material.

Within this particular application, the plasma arc initiates the transformation of carbon-rich waste materials into a synthesis gas (syngas), predominantly comprised of hydrogen and carbon monoxide. This syngas serves as a valuable resource for generating energy through a variety of means, including reciprocating engine generators, gas turbines, and steam boilers within the integrated gasification combined cycle (IGCC) framework: “The H2 and CO generated during the gasification process can be a fuel source. Therefore, plasma gasification process has been combined with many other technologies to recover energy from the syngas” [5, p. 6], as well as potentially serving as a precursor to produce liquid fuels. [5, p. 13].

IV. VIRTUES, FLAWS, & GENERAL PERFORMANCE

The analysis of this system is going to commence with its benefits or positive aspects, subsequently proceeding to address the drawbacks or negative facets, concluding with a comparative evaluation of the subjects of study.

The system possesses various advantageous attributes: it is a waste-utilizing one, thus reducing the amount of scattered waste materials; it generates sustainable energy, yielding minimal levels of pollution; the material conversion process shows high energy efficiency, as it has low energy consumption; through the plasma-based procedure, bigger control can be had over gas and toxic compounds emissions, contributing to a cleaner and safer environment; by transforming the organic waste into useful resources, it acts as booster of the circular economy by closing the material lifecycle loop.

On the other hand, it also presents some drawbacks such as a high initial investment cost for its installation; a need of superior skilled maintenance personnel, who will also take care of operating the complex technology; an exhibition of deficiencies in terms of regulatory compliance and control.

Putting the positive and negative aspects side to side, it becomes evident that the former are more meaningful and impactful than the latter. Contaminant particle generation deserves a deepening: drawing from the experiments carried out by the Georgia Tech PARF lab [7, p. 9] on MSW break down using their own plasma gasification units, the results are as follows:

1) The ex-situ experiment exhibited an impressive 84% weight loss of MSW constituents post plasma treatment, whereas the in-situ experiment, simulating real landfill conditions by incorporating soil, displayed a substantial 59% weight loss.

2) Volume reduction showed a remarkable 95.8% for ex-situ experiments, while in-situ experiments, influenced by soil vitrification, resulted in an 88.6% reduction.

3) Toxicity leaching analysis indicated heavy metals (Arsenic, Barium, Cadmium, Chromium, Lead, Mercury, Selenium, and Silver) to be below detectable levels in both experiments, well below permissible US EPA standards.

4) Output gas composition, illustrated in [6, Fig. 4] outlines the syngas compositions in parts per million for experiments with and without soil, offering insights into the resulting syngas under distinct conditions.

Output Gas	**Ex-Situ Experiment without soil (PPM)**	**In-Situ Experiment with soil (PPM)**
Hydrogen (H_2)	>20,000	>20,000
Carbon Monoxide (CO)	100,000	>100,000
Carbon Dioxide (CO_2)	100,000	90,000
Nitrogen Oxides (NO_x)	5,000	>4,500
Hydrogen Sulfide (H_2S)	100	80
Hydrogen Chloride (HCL)	5,000	>4,500
Hydrocarbons	>5,000	>4,500

Fig. 4. Output gas composition. [6]

In the comparison with other energy generation methods, as seen in [5, Fig. 5], it stands clear that the plasma-based process generates the least amount of waste. This makes it a more sustainable energy generation method than the conventional ones.

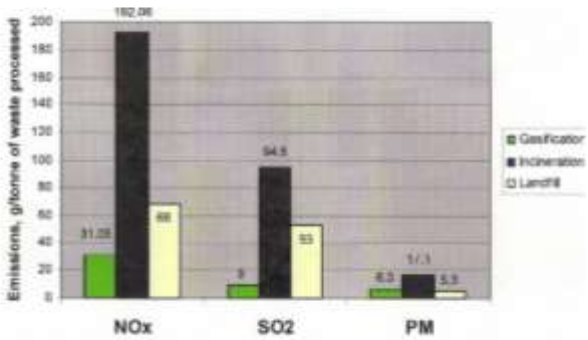

Fig. 5. Emissions in grams per ton of waste processed by different processes. [5]

V. Conclusion

Through this highly theoretical explanation, the goal is to provide a deep understanding of the operation of said innovative technology, emphasizing its relevance in waste treatment, with the hope of increasing its recognition and dissemination. The integration of this technology into the global context of sustainable development brings society closer to a cleaner and more sustainable future. By simultaneously addressing issues related to waste management and clean energy production, a significant step toward creating a healthier and more environmentally balanced world is being taken. This technology not only has the potential to reduce the amount of accumulated waste but also contributes to energy generation in a more sustainable manner, reducing dependence on non-renewable and polluting energy sources.

It is essential to delve into the development of this technology to optimize the process, making it more efficient and economically accessible. Additionally, there is a need to focus on increasing public awareness and education about this technology. Ultimately, its adoption and improvement are crucial for addressing the current challenges of urbanization and industrial expansion in a responsible and effective manner.

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