

The State of the Art in Hydrocarbon Cracking and Reforming for Hydrogen Production Using a Microwave Plasma Torch

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Abstract: *This review comprehensively synthesizes the state of the art in hydrocarbon cracking and reforming for hydrogen production using a microwave plasma torch. It critically differentiates its capabilities from other plasmas, analyzes the fundamental reaction mechanisms and scalability drives, and provides a detailed assessment of its techno-economic and environmental potential.*

Keywords: Plasma, Microwave Plasma Torch, Hydrogen Production, Hydrocarbon Cracking, Hydrocarbon Reforming

1. Introduction

The global energy landscape is undergoing significant transformation as societies seek to mitigate climate change and transition toward a low-carbon and sustainable future [1, 2]. A key component of this transition is hydrogen, which is considered a clean energy carrier. Hydrogen is particularly attractive for hard-to-abate sectors such as heavy industry and long-distance transportation [3, 4] due to its high energy density and carbon-free end-use emissions. However, the environmental benefits of a hydrogen economy depend strongly on the method of hydrogen production. Globally, more than 95% of hydrogen is currently produced from fossil fuels. Most of this hydrogen is produced through Steam Methane Reforming (SMR). This process generates approximately 9–12 kg of CO₂ per kilogram of H₂ produced. In contrast, green hydrogen can be produced with minimal greenhouse gas emissions. It is typically produced through water electrolysis powered by renewable electricity [5, 6]. However, its production remains relatively expensive and places additional demand on renewable electricity resources [7, 8]. As a result, a significant "clean hydrogen gap" persists between current production capacity and future demand [9].

The petroleum refining industry is currently facing substantial economic and technological challenges. The increasing electrification of transportation is expected to reduce demand for conventional transportation fuels [10]. Consequently, greater attention has been directed toward the Crude-to-Chemicals (CTC) concept. The objective is to maximize the direct conversion of crude oil into valuable chemical feedstock [11, 12]. Conventional technologies such as Fluid Catalytic Cracking (FCC), which are primarily designed for fuel production, are associated with significant emissions and environmental concerns [13, 14]. Therefore, reliance on such conventional processes is increasingly being questioned. Accordingly, there is a growing need for innovative technologies capable of producing clean hydrogen while enabling the sustainable utilization of hydrocarbon resources. The warm plasma reactor [15] is a plasma-based technology capable of converting methane into syngas and hydrocarbons into hydrogen-rich products. Plasma consists of a partially ionized gas containing electrons, ions, radicals, and other reactive species. Importantly, plasma can sustain highly

energetic electrons while maintaining a relatively low bulk gas temperature. As a result, chemical bonds can be selectively dissociated with limited thermal input. Hydrocarbons can be converted into various fuels and value-added products through several processing routes. Hydrogen and unsaturated C₂ hydrocarbons can be produced through the direct plasma activation of liquid hydrocarbons [19]. High-pressure plasma discharge systems [20] can facilitate hydrocarbon conversion while minimizing CO₂ emissions and enhancing hydrogen production. Hydrogen and nanostructured carbon materials can be co-produced through the plasma pyrolysis of mixed hydrocarbon gases [21].

- **Dielectric Barrier Discharge (DBD) Plasma Torches:** DBD systems generate non-thermal plasma by applying electrical discharges between electrodes separated by a dielectric barrier [22]. These systems are effective for hydrocarbon activation, with methane conversion efficiencies reported to reach approximately 47% under suitable operating conditions [23,24]. Despite these advantages, the industrial scale-up of DBD reactors remains challenging because of limitations in energy efficiency and power density [25, 26].
- **Gliding Arc and Thermal Plasma Torches:** These systems can effectively convert methane into syngas [15,27]. However, electrode degradation remains a significant challenge in such systems. Over prolonged operation, electrode erosion can reduce process stability, decrease reactor performance, and increase maintenance requirements [28–29].

The Novelty and Differentiating Excellence of the Microwave Plasma (MW) Torch

Microwave plasma torch stands out of among plasma technologies because of its unique advantages, which position it at the forefront of research aimed at industrial applications [30, 31]. Microwave plasma torches utilize microwave energy to ionize gas, generating plasmas characterized by high electron densities and temperatures, which result in high dissociation efficiencies [32].

- **Electrodeless Design and Superior Reliability:** The fundamental novelty of the MW plasma torch lies in its electrodeless design. Unlike DBD and gliding arc systems, it generates a discharge using microwave energy in a resonant cavity, eliminating internal electrodes [31]. This

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eliminates electrode erosion as a failure mechanism, ensuring long-term operational stability and preventing product contamination, thereby offering a significant advantage for continuous industrial operation [33, 34].

- **High Power Density and Efficient Energy Coupling:** Microwave energy enables volumetric and rapid heating, generating plasmas with exceptionally high power densities that promote efficient hydrocarbon dissociation within compact reactor configurations [35]. Hrycak et al. [36] demonstrated a methane conversion rate of 95.3% during steam reforming using a 915 MHz microwave plasma system. Similarly, Balyan et al. [37] reported the efficient conversion of methane into hydrogen and carbon nanotubes (CNTs) through a two-step process involving microwave plasma treatment followed by microwave-catalytic conversion of intermediate acetylene within a single microwave-driven reactor. Furthermore, significant hydrogen yields have been achieved through ethanol decomposition in microwave plasma torches [38, 39].
- **Inherent Scalability and Process Intensification:** The modular architecture of MW plasma torches is a key factor underpinning their industrial applicability. Industrial-scale deployment can be achieved through a "numbering-up" strategy, whereby multiple identical torch modules are integrated within a single reactor vessel [40]. This approach reduces the risks associated with technological scale-up while providing greater flexibility in plant design. Furthermore, this technology with the potential to replace large-scale SMR furnaces or FCC units with compact, electrically driven reactor system [41-43].
- **Synergy with Renewables and Value-Added Co-Products:** As an entirely electrical process, the MW plasma torch offers a direct pathway to deep decarbonization when powered by renewable electricity [44]. Moreover, under optimal conditions, the process co-produces solid carbon (e.g., carbon black or nanotubes) instead of CO₂ [45]. This creates a secondary revenue stream, significantly improving the business case and enabling the production of "turquoise" hydrogen [46, 47].

Industrial Relevance and Commercialization Potential

The technical advantages of the microwave plasma torch translate directly into attractive commercialization opportunities. Plasma-assisted hydrocarbon cracking offers a potentially cost-effective route for hydrogen production by utilizing existing hydrocarbon resources while reducing emissions [5]. Furthermore, its energy performance has been reported to be competitive with conventional SMR processes [6, 15]. Potential startup and deployment models include:

- 1) **Technology Licensing:** A business model focused on advancing reactor design and process optimization through continued research and development, with commercialization achieved through technology licensing agreements with established energy and engineering companies.
- 2) **Distributed Hydrogen and Carbon Production:** Deploying containerized and modular MW plasma systems at methane source locations to produce hydrogen for regional energy applications and solid carbon products for local industrial markets [48, 49].
- 3) **Refinery Integration for Chemical Upgrading:** Integrating MW plasma technology into

refinery operations to convert low-value heavy hydrocarbon fractions into higher-value light olefins and hydrogen [50], thereby supporting the transition toward crude-to-chemicals transition [11, 12].

Current research efforts are increasingly focused on moving beyond proof-of-concept studies and addressing the challenges associated with large-scale commercialization. Key research priorities include optimizing the processing of complex real-world feedstocks [51,52], conducting rigorous techno-economic analyses (TEA) and life-cycle assessments (LCA) [53–58], and demonstrating long-term operational stability in integrated pilot-scale systems [59, 60]. By addressing these challenges, microwave plasma reforming has the potential to evolve from a promising laboratory-scale technology into a key enabling platform for a sustainable and circular hydrocarbon economy.

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