

Contents lists available at [ScienceDirect](https://www.sciencedirect.com)Journal of CO₂ Utilizationjournal homepage: www.elsevier.com/locate/jcouEditorial: Special issue on CO₂ utilization with plasma technology

Plasma technology has advanced significantly in recent years, with application ranging from chemical conversion, to surface treatment, material development and several other fields. Special attention has been paid to the development of possible novel approaches for the conversion of chemicals in a more sustainable way. Plasma technology offers advantages over thermochemical routes such as high process versatility, mild reaction condition, one-step synthesis, fast reaction and instant control. More importantly, it can be easily combined with electricity generated from various renewable sources and is suitable for energy storage via the conversion of intermittent renewable energy into carbon-neutral fuels or other chemicals. In recent years, there has been a growing interest in the development of plasma technology for CO₂ utilization. Investigation on different reactions such as CO₂ splitting, dry reforming of methane (DRM) and CO₂ hydrogenation with different types of plasma reactors and catalysts have been reported by researchers worldwide. Although technological maturity still needs to be increased, the potential of plasma has been well-recognized by the scientific community and industry. More research output in the future is expected as a result of intensive research activities and various kinds of investment. In this context, we present this special issue on CO₂ utilization with plasma technology, which collects 22 articles, covering topics in related areas such as plasma reactor design, plasma catalysis, plasma-material interaction, modeling and new ideas for possible applications.

1. The collection of papers

Two review articles are included in this special issue. Chen et al. reviewed the main theoretical aspects as well as the most recent achievements in the field of CO₂ conversion by non-thermal plasma [1]. With a special accent on the advantage of plasma catalysis, they systematically analyzed different plasma processes and catalyst materials. Discussion on further progress and potential application has also been made to provide directions for future research. Centi et al. conducted a concept review that analyzes the CO₂ splitting to carbon by possible technical solutions [2]. This “dream reaction” will be a good tool to address the issue of greenhouse gas emissions but realizing it in practical situations remains a big challenge. The authors discussed non-thermal plasma in combination with catalysts as a promising approach. By analyzing the current status of plasma-based CO₂ splitting and proposing conceptual ideas, this paper can stimulate research in this field and promote the generation of alternative possibilities.

The design of plasma reactors plays a crucial role in CO₂ conversion and is a key research direction at this moment. Depending on the reaction and the type of plasma discharge, different kinds of reactors have been reported in papers collected by this special issue. Mei et al. made a

comparison between single-dielectric and double-dielectric DBD reactors through experiments on CO₂ reforming of CH₄ [3]. Measurements on the temperature, electrical and optical characteristics and related discussion were made to explain the difference in reactor performance regarding CO₂ conversion, selectivity of the liquid and gaseous products as well as carbon deposition. Martin-Del-Campo et al. developed a rotating gliding arc-spouted bed reactor for the DRM at atmospheric pressure [4]. Two Ni-based catalysts with different loadings were tested to investigate the plasma-catalyst interaction. Several interesting results have been observed, including increased selectivity towards H₂ and CO, as well as a significant decrease in carbon deposition on the electrode, indicating the potential of this type of reactor to be used for plasma-catalytic reactions. In the study by Chen et al., a fluidized-bed DBD reactor was developed and compared with the packed-bed DBD reactor [5]. It was found that the forward reaction was promoted by the generation of DBD in the fluidized bed reactor, but the reverse reaction was not influenced. Those two papers provide a different point of view than classical packed-bed DBD reactors for the coupling of plasma with catalyst.

It has been shown in many previous studies that microwave plasma has a good performance for the splitting of CO₂ at low-pressure conditions. Hecimovic et al. investigated the CO₂ conversion in a microwave plasma torch equipped with a nozzle in the pressure range of 100–900 mbar [6]. The obtained results showed that with the nozzle, it is possible to increase the conversion and energy efficiency at high pressure towards values achieved at low pressure. Such enhancement is highly beneficial, considering the industrial application of this technology.

Renninger et al. investigated CO₂ splitting in a DC atmospheric pressure discharge reactor [7]. An improved configuration, optimized gas flow and external magnetic field were applied to achieve high splitting efficiency and to study the scaling effect involved in the process. In the paper of Wanten et al., a confined atmospheric pressure glow discharge plasma reactor was used for DRM and good performance was achieved (conversion of 64% and 94% for CO₂ and CH₄ and energy cost of 3.5–4 eV/molecule) [8]. A quasi-1D chemical kinetics model was also developed to discuss the reaction pathways and formation of different products. Trenchev et al. reported their study of CO₂ splitting using atmospheric glow discharge reactors [9]. Three different reactor configurations were tested, and the plasma properties were also studied by using an advanced model.

Besides the reactor design, it is also worth looking into the plasma operation schemes and conditions. Soldatov et al. reported their work on ultrafast microwave pulsing of a plasma torch [10]. The pulsation parameter was scanned along with plasma diagnostics to analyze the mechanism that limits the CO yield, and models were built to give

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insights into the gas flow dynamics. Silva et al. studied the time evolution of CO₂ dissociation in a pulsed discharge through kinetic modeling [11]. They used their model to analyze the effect of pulse configurations and revealed the importance of electronically excited states in the CO₂ dissociation process. In the paper of Van Alphen et al., the effect of N₂ on CO₂-CH₄ conversion in a gliding arc plasmatron was reported, and a combination of four computational models was used to discuss the benefits of N₂ addition [12]. Considering the practical application of plasma, this research finding is important since N₂ exists in most industrial gas emissions.

In the plasma-catalytic conversion of CO₂, the performance of catalysts is of great importance and the effect of material properties needs to be understood. This was the goal of the research conducted by Kaliyappan et al. who investigated the properties of core-shell SiO₂@-TiO₂ spheres in a packed-bed DBD reactor [13]. The preparation condition of the shell and the morphology of the core-shell introduced surface changes that influenced the CO₂ dissociation. Cheng et al. developed a novel plasma catalysis model by coupling CO₂ plasma and surface reactions on Ni/ γ -Al₂O₃ [14]. Their model suggested that vibrationally excited CO₂ molecules can be efficiently dissociated on the surface of the catalyst, and increasing the population of the vibrational levels would improve the plasma-catalytic efficiency. In the paper from Li et al., plasma-catalytic conversion of CO₂/CH₄ into oxygenates was investigated by using a series of nickel foam supported Ni catalysts [15]. The authors showed that surface microstructure and valence state can efficiently modulate the distribution of oxygenates produced. The role of catalysts in plasma-catalytic hydrogenation of CO₂ was studied by Ashford with the target of C₂H₆ production [16]. Several alumina-supported catalysts, including Ru, Cu, Ni and Fe, were tested and the highest selectivity was obtained with the Ru catalyst. In the paper from Gorky et al., metal organic framework (MOF)-177 was used in the plasma reactor as CO₂ and CH₄ adsorbent and plasma-induced desorption was reported [17]. In addition, plasma-catalytic methanol synthesis from CH₄ oxidation with O₂ and CO₂ has also been investigated.

Besides CO₂ conversion through plasma-induced chemical reactions, there are also other indirect ways in which plasma can be applied. As a novel tool for catalyst preparation, the plasma process could be used to synthesize or modify catalysts for the conversion of CO₂, and an improvement in catalyst performance is often achieved. Woldu et al. reported their study of Ar-plasma treatment on Au film for electrocatalytic conversion of CO₂ to CO [18]. This treatment method is capable of creating new active sites of under-coordinated facet with open structure, Au (311), lower surface work function and increased electrochemical surface area. In the research conducted by Dai et al., DBD plasma was used to prepare ceria-zirconia solid solution supported Ni catalyst via decomposition of nickel precursor, and a comparison was made with catalysts prepared by conventional thermal decomposition method [19]. Several advantages of plasma-prepared catalysts were observed, including smaller Ni particle size, higher reducibility, more basic sites and oxygen vacancies which promote CO₂ activation. In addition, highly reactive carbon can be formed on the surface of the plasma-prepared catalyst during the DRM process, leading to better coke resistance.

Moreover, other possibilities can be generated in the area of material synthesis and modification. Ekanayake et al. proposed a plasma-assisted approach to synthesize carbon-MgO nanohybrids for CO₂ capture [20]. In this method, the carbon source was provided by biomass and the MgO was derived from plasma-electrified seawater. Considering the plasma is powered by renewable electricity, this material recovery process demonstrates the potential of plasma for application in a "power-to-decarbonization" scenario.

Another important application is to use CO₂ as the gaseous medium for the plasma treatment of materials. Lin et al. used CO₂/N₂ DBD plasma to modify the surface of polytetrafluoroethylene (PTFE) membranes and investigated the effect of different CO₂ concentrations and

exposure time [21]. Their study provided useful insight for CO₂ plasma treatment to induce the formation of carboxylic groups on treated polymer surfaces. Another study by Kang et al. used CO₂ and low-density polyethylene powder as the reactants in a rotating gliding arc plasma reactor [22]. The reduction of CO₂ and upcycling of plastic powder were achieved in this process, demonstrating a new area of possible application.

Acknowledgment

Overall, plasma technology has great potential in CO₂ utilization and progress in research has been made during the past few years. We hope this special issue, with the topics and depth it covered, could serve as a stepstone to the next step development of this technology. With the continuous efforts of researchers around the world, higher energy efficiency in CO₂ conversion, a better understanding of the mechanisms and a wider range of applications can be expected in the future. At last, we would like to thank all the authors, reviewers and editors who participated in the publication of this special issue.

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