Research Progress in Electrochemical Technology for Reducing Carbon Dioxide

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Abstract. With the elevated carbon dioxide (CO_2) emissions and the need for green and sustainable development, the need for electrochemical CO_2 reduction technology is becoming more and more urgent. However, the electrochemical reduction technology still has difficulties and has not yet met the high requirements for large-scale industrialized production. In this paper, the field of electrochemical reduction of carbon dioxide is deeply explored from the perspectives of technological features and applications, and the progress in this field is discussed in terms of cathode materials, anode materials, and electrolytes, and the application of electrochemical technology in the field of carbon dioxide reduction is investigated concerning the differences in the generating material and loading voltage. Electrochemical carbon dioxide reduction technology can reduce carbon dioxide into utilizable industrial products by loading load voltage, and can selectively generate products such as formic acid, methanol, and methane by choosing different electrode materials and electrolytes, the selection of electrode materials and electrolytes and the selection of suitable load voltage are also the technical difficulties and the key points to realize industrial production. The electrochemical reduction of carbon dioxide technology has a wide range of applications in industrial production and energy saving and emission reduction, and this paper provides ideas for the understanding and further development of electrochemical reduction of carbon dioxide technolog.

Keywords: Electrochemistry, carbon dioxide reduction, electrode material, electrolyte.

1. Introduction

With social progress and the development of science and technology, the use of traditional fossil fuels is unavoidable in the context of mankind's ever-increasing demand for productivity, which at the same time causes a large amount of carbon dioxide emissions, which brings about many problems related to environmental pollution, and the most familiar is the greenhouse effect, where a large amount of carbon dioxide emissions lead to an increase in the temperature of the environment, which is closely related to each person.

By reducing CO_2, we can convert CO_2 into energy, which not only reduces the greenhouse effect and global warming but also recycles CO_2 and reduces the pressure on limited resources. At the same time, this can also promote sustainable development and reduce the dependence on traditional fossil fuels. The most important point is that carbon dioxide, as a common gas, can be considered inexhaustible. It is thus evident that carbon dioxide reduction has high research value and wide application prospects in its field of study. Electrochemistry is the study of electric potential and its related chemical reactions, by applying voltage and other methods to promote the reaction, the reduction of carbon dioxide by electrochemical methods has become a hot spot of research, and the selection of electrode materials and catalysts, increased the solubility of carbon dioxide in the solvent and enhance the selectivity of the product is the main direction of research.

The electrochemical reduction of carbon dioxide technology has a wide range of applications in realizing environmental protection, energy saving and emission reduction, and industrial production. The influence of each technical index of the electrochemical reduction technology of carbon dioxide on the reaction process is discussed in the whole paper, and the production of products such as methane, formic acid, and formaldehyde under different loading voltage conditions is realized using different electrode materials and electrolytes. In the field of environmental protection, electrochemical reduction of carbon dioxide is also a useful means of consuming greenhouse gases,

and it has a broad application prospect to convert polluting gases into energy and industrial products. At present, the electrochemical reduction of carbon dioxide technology still has the problems of low reaction selectivity and current utilization efficiency, and in the future, the researchers will improve the technology for the above deficiencies and realize the large-scale production and application. This paper puts forward some suggestions for the wide application and further development trend of the electrochemical reduction of carbon dioxide technology.

2. Carbon Dioxide Reduction Technology

2.1. Common Reduction Technologies

The combustion of conventional fossil fuels results in the production of carbon dioxide (CO_2), a greenhouse gas. However, carbon dioxide is also a plentiful, renewable, and inexpensive carbon resource. Converting it into chemical products with high added value is a way to realize turning waste into treasure. Thermochemical reduction, photochemical reduction, photo electrocatalytic reduction, and electrochemical reduction are the main CO_2 conversion and usage technologies at the moment. The thermochemical reduction process, however, has a number of drawbacks, including an excessively high reaction temperature, the inability to directly separate some by-products, and the requirement for increased catalyst activity and stability in actual commercial applications. The photochemical reduction method and photo electrocatalytic reduction method are energy-saving, non-polluting, and mild reaction conditions, but still have the problems of solar energy utilization and low conversion efficiency.

To solve these problems, researchers are exploring new CO_2 conversion and utilization technologies. Among them, the biocatalytic method has received widespread attention as a green and sustainable method. The biocatalytic method utilizes biocatalysts such as enzymes to catalyze the conversion of CO_2, with mild reaction conditions, high selectivity, and high added value of the products. In addition, biocatalysis can utilize renewable resources such as glucose as a reductant to achieve a carbon-neutral cycle. In addition to biocatalytic methods, researchers are also exploring nanotechnology-based CO_2 conversion methods. Nanotechnology can provide new materials and devices with excellent physical, chemical, and biological properties. For example, nanocatalysts can provide efficient CO_2 conversion activity, and nanocapture materials can effectively separate byproducts. Nanotechnology can also provide efficient energy conversion and memory devices, such as nano-solar cells and nano-fuel cells, for efficient CO_2 utilization.

In summary, CO_2 conversion and utilization technologies are constantly evolving, including thermochemical reduction, photochemical reduction, photo electrocatalytic reduction, electrochemical reduction, biocatalytic methods, and nanotechnology-based methods. Each of these methods has its advantages and disadvantages, and researchers will continue to explore new methods to achieve efficient conversion and utilization of CO_2 for sustainable development.

2.2. Electrochemical Technology

In comparison, the advantages of electrochemical reduction are the follows: (i) the ability to regulate the reaction process and target products by controlling the electrolysis conditions, resulting in products with better performance and higher purity; (ii) high conversion efficiency, simpler unit reaction, reduced occurrence of side reactions, and improved product yields; (iii) recycling and utilization of CO_2, synthesis of fine chemicals, reduced carbon emission and is favorable to environmental protection; (iv) clean energy is used in the reaction, which reduces the emission of waste gas and water and lowers the pollution to the environment.

Electrochemical reduction technology has a wide range of application prospects. In the chemical industry, electrochemical reduction technology can be used to synthesize high-purity organic compounds, such as alcohols, aldehydes, acids, etc. It can also be used for the preparation of metal-organic compounds. In addition, electrochemical reduction can also be used in the metallurgical industry, through the electrolytic process of metal cation reduction into metal, with energy saving,

environmental protection, and other advantages. In the field of energy, electrochemical reduction technology can also be used to prepare new energy devices such as solar cells and fuel cells to improve the efficiency of energy utilization [1].

3. Electrochemical Techniques for Carbon Dioxide Reduction

3.1. Technical Characteristics

Electrochemical carbon dioxide reduction technology offers several advantages. The technology is environmentally friendly, as CO_2 reduction reduces pollution by converting industrial emissions into useful chemicals or fuels. The technology is also highly efficient, as the high energy conversion efficiency of electrochemical technology helps to reduce industrial production costs. In addition, the technology has a wide range of applications, and carbon dioxide reduction technology is suitable for a variety of scenarios, as well as other hot areas.

In electrochemical technology, the key factors for carbon dioxide reduction are the selection of electrode materials and catalysts. Different electrode materials and catalysts affect the reaction process and product selectivity of carbon dioxide reduction. For example, the use of electrode materials with high electrical conductivity and high surface area can increase the adsorption of carbon dioxide on the electrode and improve the reaction rate and product yield. Meanwhile, the choice of catalyst is also very important to accelerate the reaction process and improve the product selectivity. In addition to the choice of electrode materials and catalysts, the nature of the electrolyte also affects the reaction process and products of carbon dioxide reduction. For example, in alkaline electrolytes, carbon dioxide reduction mainly produces organic compounds such as methanol and formic acid, while in acidic electrolytes, carbon dioxide reduction mainly produces carbon-containing organic compounds such as carbon monoxide. In addition, electrochemical technology can also control the electrolysis conditions to regulate the reaction process and target products. For example, changing the concentration of electrolyte, electrolysis voltage, electrolysis time and other conditions can affect the reaction rate and product selectivity, as shown in Table 1. In addition, electrochemical technology can also realize the recycling of carbon dioxide conversion and utilization, reduce carbon emissions, and be conducive to environmental protection.

Table 1. Reactions and potentials of CO_2 electrochemical reduction reactions [2]

Electroreduction Reaction Equation	electrode potential/V (vs. NHE)
$CO_2 + 2H^+ + 2e^- \rightarrow CO + H_2O$	-0.52
$CO_2 + 2H^+ + 2e^- \rightarrow HCOOH$	-0.61
$CO_2 + 4H^+ + 4e^- \rightarrow HCHO + H_2O$	-0.51
$CO_2 + 6H^+ + 6e^- \rightarrow CH_3OH + H_2O$	-0.38
$CO_2 + 8H^+ + 8e^- \rightarrow CH_4 + 2H_2O$	-0.24
$2CO_2 + 12H^+ + 12e^- \rightarrow C_2H_4 + 4H_2O$	-0.34

3.2. Electrode Materials

Anode materials are a key part of electrochemical CO_2 reduction technology, and they are of various types with different advantages and disadvantages. At present, the main cathode materials studied include metal oxides, metal sulfides, and noble metals. These positive electrode materials are different in terms of efficiency, stability, and cost in the reduction process, so they need to be selected according to the specific needs in practical applications.

Negative electrode materials play the role of storing and releasing electrons in electrochemical carbon dioxide reduction technology. Common negative electrode materials include graphene, metal oxides, metal sulfides, and so on. Graphene has good electrical conductivity and stability, but is more costly; metal oxides and metal sulfides are less costly, but are prone to volume changes during charging and discharging, leading to structural instability. Future research directions may include searching for more efficient and stable negative electrode materials and researching new composite

materials. As shown in Table 2, the selection of different electrode materials has a regulatory effect on the reaction products.

Table 2. Reactions and potentials of CO_2 electrochemical reduction reactions [3-6]

Electrode type	metals	Main reduction products
Electrodes with high hydrogen potential	Bi, Pb, Sn, Hg, In, Cd	HCOOH
Electrodes with medium hydrogen potential	Pd, Ag, Zn, Ga, Au	CO
Electrodes with low hydrogen potential	Ti, Ni, Fe, Pt	H_2
Hydrogen Suppression Reaction Electrode	Cu	CH_4, C_2H_4

3.3. Electrolyte

The electrolyte plays the role of transporting electrons and ions in the electrochemical CO_2 reduction technique. The products of electrochemical CO_2 reduction in aqueous solution are related to the potential (electromotive force) and the electrode, with CO and carboxyl groups being the main products in larger negative potentials and CH_2 and C_2H_4 being produced in smaller negative potentials [7-9].

Water is the most commonly used electrolyte because of its abundance in nature and low cost. However, the use of pure water electrolytes may lead to problems such as low electrolysis efficiency and poor selectivity of CO_2 products. Therefore, researchers usually add some co-solvents such as carbonate, bicarbonate, or ammonia to water to improve the electrolysis efficiency and selectivity.

Aqueous solutions of carbonates or bicarbonates can improve the selectivity of the reaction because they can form stable compounds with CO_2. However, the use of these electrolytes can lead to side reactions, such as carbonate formation, which can reduce electrolysis efficiency. Ammonia is another commonly used electrolyte to improve the selectivity and stability of CO_2 reduction. The CO_2 in the ammonia electrolyte can combine with ammonia to form ammonia-conjugated carbonate (NH_4CO_3), which improves the efficiency of CO_2 reduction.

In addition to the electrolytes mentioned above, there are many other electrolyte options such as formate, oxalate, acetate, etc.

4. Applications and Outlook

4.1. Applications

The subject of energy storage and conversion currently contains many examples of uses for electrochemical carbon dioxide reduction technologies. A promising approach for turning CO_2 into useful compounds is electrochemical reduction.

Formic acid, methanol, CO, methane, H_2, etc. are the primary byproducts of the electrochemical reduction of CO_2. The electrochemical conversion of CO_2 to formic acid has a wide range of potential applications and directions for research since formic acid is a particularly adaptable organic raw material [10].

In addition, sugars and biofuels can be made as well as greenhouse gas emissions reduced by the electrochemical reduction of CO_2, which has a significant impact on industrial production and environmental protection domains. The technology for electrochemical carbon dioxide reduction is essential for regulating the greenhouse effect and lowering pollutants in the field of environmental protection. In industrial production, electrochemical CO_2 reduction technology can effectively reduce costs and improve energy efficiency, while ensuring consistent product quality. In addition, the technology can help develop a new generation of clean energy sources, such as renewable hydrogen, thus promoting the global energy transition and contributing to the realization of the Sustainable Development Goals (SDGs).

The efficient utilization of electrochemically reduced carbon dioxide also has great potential in the field of bio-agriculture. It can convert carbon dioxide into nutrients needed for plant growth, thereby increasing crop yields and reducing dependence on chemical fertilizers. In addition, CO_2 reduction

technology could help develop new and efficient fertilizers to meet the growing global demand for food. In terms of food security, the technology will have a positive impact on guaranteeing the stability of the global food supply chain and reducing hunger.

4.2. Outlook

In the future, with the continuous development and maturity of electrochemical carbon dioxide reduction technology, the application areas will continue to expand. For example, in the field of renewable energy, the conversion of renewable energy sources such as solar energy and wind energy into chemical fuels using carbon dioxide conversion technology can improve the efficiency of energy utilization; in the field of construction, the production of building materials utilizing carbon dioxide conversion technology can reduce the energy consumption of buildings; and in the field of agriculture, the production of nutrients required for crop growth through carbon dioxide conversion technology can improve crop yields. In addition, the technology can be used to prepare hydrogen, and synthesize methanol and other fuels. Future research directions include improving electrochemical reduction efficiency, reducing equipment costs, optimizing electrolyte formulations, exploring new catalysts, and developing sustainable electrochemical carbon dioxide conversion technologies. Combining carbon dioxide reduction technology with other renewable energy technologies to realize comprehensive utilization is also a research direction worthy of attention.

Through in-depth research on carbon dioxide reduction technology, the conversion mechanism of carbon dioxide can be better understood, providing strong support for solving the problems of global climate change and resource constraints. With the continuous progress of technology, electrochemical carbon dioxide reduction technology will become an important means of energy conversion and storage, contributing to sustainable development and green energy utilization.

5. Conclusion

The electrochemical reduction of carbon dioxide technology has a wide range of applications in realizing environmental protection, energy saving and emission reduction, and industrial production. The whole paper discusses the influence of each technical index of the electrochemical reduction technology of carbon dioxide on the reaction process, which realizes the production of products such as methane, formic acid, and formaldehyde under different loading voltage conditions using different electrode materials and electrolytes. With a wide range of potential applications for converting harmful gases into energy and industrial products, electrochemical reduction of carbon dioxide is a helpful method of consuming greenhouse gases in the field of environmental protection. Low reaction selectivity and current usage efficiency remain issues with the electrochemical reduction of carbon dioxide technology at this time, and in the future, the researchers will improve the technology for the above deficiencies and realize the large-scale production and application. This paper makes some recommendations for the widespread use and continued advancement of the electrochemical technology for carbon dioxide reduction.

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