

Process-Intensified Technologies for Industrial Carbon Dioxide Utilization

Under increasing global efforts to mitigate climate change, industrial carbon dioxide emissions have become a major focus of greenhouse gas reduction strategies. Beyond carbon capture and storage, the utilization of carbon dioxide as a resource is widely regarded as an effective approach for enabling industrial low-carbon transition and circular economy development. Industrial CO₂ utilization converts captured carbon dioxide into fuels, chemicals, or functional materials, reducing net emissions while creating additional economic value. However, conventional CO₂ utilization processes often suffer from low reaction rates, high energy consumption, and limited scalability, which hinder their large-scale industrial implementation.

Process intensification technologies offer promising solutions to these challenges by enhancing mass transfer, heat transfer, and reaction efficiency within compact systems. Common intensification approaches include microreactors, multiphase reaction coupling, catalyst structure optimization, and reaction–separation integration. These techniques significantly improve CO₂ conversion efficiency, reduce energy demand, and decrease equipment size. In industrial applications, process intensification not only enhances reaction performance but also improves system flexibility and operational stability, facilitating the scale-up and deployment of CO₂ utilization technologies.

This study systematically investigates process-intensified technologies for industrial carbon dioxide utilization. By developing coupled models of reaction kinetics and transport phenomena, the effects of different intensification strategies on CO₂ conversion efficiency, energy consumption, and system performance are analyzed. Furthermore, the engineering applicability of process intensification in representative industrial scenarios—such as methanol synthesis, synthetic fuel production, and chemical manufacturing—is evaluated. The results provide theoretical insights and engineering guidance for optimizing process design and selecting appropriate technologies for industrial CO₂ utilization.

The findings support the advancement of process intensification in carbon resource utilization, contributing to industrial emission reduction, efficient resource use, and sustainable low-carbon development. This research promotes the transition of industrial systems toward greener and more circular production pathways.