Abstract

Coiled Flow Inverter-Assisted Heterogenous Catalysis for Sustainable Energy and Environmental Remediation

The chemical industry is confronted with a critical need for efficient and scalable continuous flow processes that guarantee consistent product quality and cost-effectiveness. The advent of the coiled flow inverter (CFI) offers a novel and compact solution to address these challenges. Engineered with a helical coil comprising frequent 90-degree bends, the CFI presents a distinct geometry, holding immense promise for applications requiring optimal mixing within laminar flow conditions. Our recent studies explore the application of CFI technology in various energy and environmental processes.

The first study presents the application of CFI reactors in the adsorptive desulfurization (ADS) of liquid fuels. A copper-tartrate was synthesized as a precursor to develop Cu-carbon nanofibers (Cu-CNF), which was used as an adsorbent for thiophene in n-hexane. By employing a slurry of Cu-CNF in a series of five CFI units at a 120 cc/min flow rate and 2000 ppmw-S concentration, a high sulfur loading of 103 mg/g was achieved. A recycling mode was introduced for the first time in the CFI-based ADS, where only three CFIs with a recycle ratio of 2 matched the removal efficiency of the five-CFI setup. This demonstrates the capability of the CFI unit to not only match but exceed conventional packed bed performance, offering compactness and enhanced control.

The second study addresses the environmental concern of pharmaceutical contaminants, specifically the presence of paracetamol in aquatic systems. A CFI-based photoreactor was developed using a visible-light-active photocatalyst, Co-Ni tungstate anchored on graphitic carbon nitride (CoNiW-gCN). The CFI’s geometry enabled enhanced mixing and uniform light distribution via visible LEDs, crucial for efficient photocatalytic activity. The CoNiW-gCN catalyst was synthesized directly in the CFI, ensuring good dispersion and consistent quality. A 4 × 4 CFI configuration using a 1 g/L dose of 7.5% CoNiW-gCN achieved over 99% degradation of 10 ppm paracetamol in just 36 minutes. This performance was 2.7 times faster than that observed in conventional batch reactors, demonstrating the CFI's scalability and effectiveness for wastewater remediation via advanced oxidation processes (AOPs).

In the third study, the global need for sustainable hydrogen production was addressed by developing a cost-effective electrocatalyst for the hydrogen evolution reaction (HER). A green synthesis approach was employed within CFI to synthesize the mixed-valence Fe_xO_y nanoparticles (Fe^0, Fe_2O_3, and Fe_3O_4) doped onto g-CN, using green tea extract as a biogenic reducing and stabilizing agent. The CFI facilitated uniform dispersion, precise Fe-loading, and high-throughput catalyst production. The resulting Fe_xO_y/g-CN electrocatalyst demonstrated enhanced electrochemical performance, with an HER overpotential of 256 mV at 10 mA cm^{-2} and a Tafel slope of 154 mV dec^{-1}. It also exhibited excellent operational stability over 24 hours in 1 M KOH electrolyte. These improvements are attributed to the synergistic interaction between mixed-valence iron species and the conductive g-CN matrix, which improved charge transfer and active site availability. The study establishes the CFI-based process as a green, scalable alternative to conventional noble metal-based electrocatalysts.

The fourth study further extended the application of CFI technology to wastewater treatment, specifically nitrate removal through photo-biocatalytic denitrification. The Fe_xO_y/g-CN photocatalyst, synthesized using the same green method, was used in conjunction with a microbial biofilm to develop an S-scheme photocatalyst-biofilm system. The CFI's helical design enhanced catalyst dispersion, mixing, and photon penetration, which improved the kinetics of both photocatalytic and microbial reactions. Under visible LED light, the combined system achieved 99% denitrification efficiency within 60 minutes. The presence of the S-scheme heterojunction in the catalyst structure enabled efficient charge separation and improved redox potential, while the microbial synergy facilitated faster conversion of nitrate to nitrogen gas. This work demonstrates a sustainable and scalable approach to mitigating nitrate pollution using CFI-assisted synthesis and reactor design.

These studies underscore the versatility of CFI technology across a range of applications, from clean fuel processing to green hydrogen production and sustainable water treatment, establishing CFI as a transformative technology for future chemical processes.