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Energy-Efficient Catalytic Membrane Vacuum Regeneration for Solvent-Based Direct Air Capture

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ABSTRACT

Climate change mitigation requires scalable technologies capable of removing carbon dioxide directly from the atmosphere. Solvent-based Direct Air Capture (DAC) has emerged as a promising negative-emission technology due to its unique advantages. However, its large-scale deployment remains constrained by the high energy demand comes with solvent regeneration. In conventional solvent-based CO_2 capture processes, regeneration typically occurs at elevated temperatures (120-140 °C), requiring high-grade heat and resulting in substantial operational costs. Developing regeneration strategies that operate at lower temperatures while maintaining high CO_2 capture performance is therefore essential for enabling sustainable and economically viable DAC deployment.

This work presents the development and viability of an energy-efficient solvent-based DAC technology that integrates three advanced approaches: catalytic solvent regeneration, hybrid solvent formulations, and membrane vacuum regeneration (MVR). By combining these technologies, the regeneration process can operate at significantly lower temperatures, reducing thermal energy requirements while maintaining strong CO_2 desorption performance. Iron-modified sulfated zirconia (Fe-SZ) catalysts supported on Al_2O_3 and SiO_2 were synthesized and integrated into a low-temperature MVR system to enhance desorption kinetics and mass transfer under DAC conditions. Among the tested materials, Fe-SZ supported on SiO_2 demonstrated the most effective catalytic behavior, achieving substantial reductions in regeneration heat duty relative by 59.7%.

Further improvements were achieved through the use of amino-acid-based hybrid solvent blends. Experimental evaluation showed that blending potassium taurinate (TauK) with potassium sarcosinate (SarK) significantly enhanced CO_2 desorption compared with single-solvent systems by up to 69.1%. When combined with catalytic regeneration within the MVR unit, the whole system delivered notable improvements in both desorption performance and energy efficiency. Under representative DAC operating conditions, the integrated catalytic-membrane system achieved a sensible thermal energy requirement of approximately 2.6 GJ/tCO_2, a significantly reduction.

Based on these laboratory-scale developments, a pilot-scale DAC system has been constructed to evaluate the technology under realistic operating conditions. The containerized pilot unit,

equipped with integrated cooling towers and membrane regeneration modules, currently operates at a capture capacity of approximately 10 tCO_2/yr. Initial testing focuses on validating system performance using single-solvent operation, with future work aimed at implementing hybrid solvent systems and scaling the technology toward larger capture capacities, targeting 50 tCO_2/yr.

Overall, this work demonstrates the strong synergistic benefits of integrating catalytic regeneration, hybrid solvent chemistry, and membrane-based regeneration processes. The results highlight a promising pathway toward scalable, energy-efficient, and renewable-compatible DAC systems capable of supporting large-scale atmospheric CO_2 removal.

KEY WORDS

Direct air capture, catalytic solvent regeneration, low-temperature membrane vacuum regeneration, amino acid solvents

BIOGRAPHY

Arash Momeni is a current Research Fellow at the University of Melbourne, Department of Chemical Engineering, specializing in direct air capture (DAC) technology for carbon dioxide removal. He completed his PhD at the University of Melbourne, focusing on the development of energy-efficient solvent-based DAC systems using hollow fibre membrane modules, and catalytic solvent regeneration. His research aims to advance sustainable carbon capture processes compatible with renewable energy sources.

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