

Extended Abstract

(For Ph.D. Open Seminar)

Design and Optimization of Coiled Flow Inverters for Process Intensification in Sustainable CO₂ Capture and Organic Transformations

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Degree for which submitted: Doctor of Philosophy

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Scope of the Thesis:

Industrial growth has significantly increased CO₂ emissions, creating an urgent need for efficient capture and utilization technologies. Conventional batch reactors are limited by slow processing, high energy use, poor heat and mass transfer, and lack of real-time monitoring. While continuous flow reactors offer some improvements, challenges such as uncontrolled slug flow and absence of in-situ visualization still remain. To overcome these limitations, this thesis proposes a novel glass-based Coiled Flow Inverter (CFI) reactor. Its transparent design allows real-time observation of product formation while enhancing CO₂ capture and conversion efficiency. The work focuses on developing a continuous-flow CO₂ capture system using CFIs, along with exploring low-cost and eco-friendly absorbents such as lignin from agricultural waste and nitrogen-rich waste streams. Overall, the study aims to advance process intensification, promote sustainable materials, and enable efficient organic transformations using flow chemistry.

Chapter 1. Introduction

This chapter presents an overview of the design and application of the Coiled Flow Inverter (CFI), along with its advantages over conventional batch and flow reactors. It includes a comprehensive survey of CO₂ capture in gas–liquid as well as liquid–liquid systems. Special emphasis is given to CO₂ capture using both amine-based and non-amine-based solutions, particularly sustainable materials such as biomass. Additionally, this chapter reviews recent advancements in organic reactions for the synthesis of fluorescent materials in liquid–liquid systems and also describes the methods used for spectroscopic interpretation and microscopic data analysis are systematically outlined.

Chapter 2. Materials and Methodology

This chapter outlines the materials and reagents used for CO₂ absorption and the synthesis of fluorescent Xanthene dye in a Coiled Flow Inverter. It also provides a detailed description of the instruments and analytical techniques employed in the study. This chapter covers the synthesis procedures for CO₂ capture using both alkanolamine-based and amine-free systems, along with C–H bond formation involving gallic acid and N,N-dimethylformamide (DMF). In addition, it presents the experimental methodology for CO₂ capture and includes detailed mathematical calculations related to heat transfer processes.

Chapter 3. Hydrodynamics driven CO₂ Absorption in Coiled Flow Inverters using Amine Based Solvents

Driven by the United Nations' Sustainable Development Goals (SDGs), this study addresses the urgent need for efficient and sustainable carbon capture methods to reduce anthropogenic CO₂ emissions. Conventional batch processes using concentrated alkanolamine solutions are functional but hindered by high energy consumption and poor efficiency. To overcome these limitations, millimeter-sized coiled flow inverters (CFIs) were used as point-source CO₂ capture tools capable of continuous operation. The study found that the solvent and CO₂ gas flow rates are key parameters that govern the slug flow regime and slug lengths within the CFI, with a high interfacial area and sufficient residence time identified as the primary drivers of enhanced CO₂ absorption. Notably, an approximate 98% CO₂ absorption efficiency was achieved using a 3% aqueous diethanolamine (DEA) solution in the CFI system. Furthermore, the potential of nanocellulose, an environmentally sustainable nanomaterial, was demonstrated for CO₂ capture at low flow rates, highlighting its promise as a green alternative for carbon-capture applications.

Chapter 4. Sustainable CO₂ Capture Using Waste-Derived Absorbents in a Coiled Flow Inverter Reactor

Conventional CO₂ capture systems use synthetic amines, which are energy-intensive, corrosive, and environmentally harmful. This creates a need for greener and more efficient alternatives. This study presents a flow-based approach for CO₂ absorption using waste-derived materials in a Coiled Flow Inverter (CFI) reactor. Human urine, rich in nitrogen compounds, is used as a natural amine substitute and combined with lignin obtained from rice straw, an abundant agricultural waste. The interaction between urine components and lignin improves CO₂ absorption, while the enhanced mixing and flow inversion in the CFI reactor increase mass transfer efficiency. Under optimized conditions, the lignin–urine system achieved up to 96% CO₂ removal, outperforming conventional systems. This approach demonstrates a low-cost, eco-friendly, and scalable solution for carbon capture, aligned with circular economy principles.

Chapter 5. Intensifying the Synthesis of Xanthene Dyes from Gallic Acid using Coiled Flow Inverter

Transparent coiled flow inverters (CFIs) offer clear advantages over opaque coil reactors but have rarely been used for condensation reactions. This study addresses that gap by demonstrating the continuous-flow condensation of gallic acid in a 4 mm internal diameter CFI reactor. The length of the flow reactor is varied by connecting multiple CFIs in series, and real-time imaging of the reactor during flow synthesis provides valuable insights into reaction dynamics and the stages of desired product formation. The use of stacked CFIs ensures adequate residence time for carrying

out reactions at high flow rates, while the condensation of gallic acid in dimethylformamide (DMF) yields a green-emissive xanthene analogue, the production of which is optimized by regulating reactant flow rate and reaction temperature. The presence of a vapour–liquid phase boundary further enhances interfacial area, contributing to improved product yield, and the optimized conditions for fluorescent product formation using the stacked CFI were identified as 190°C at a flow rate of 5 mL h⁻¹, with a residence time of approximately 14 hours and a heat flux of 4.46 W m⁻² required to maximize yield. Collectively, these findings demonstrate that CFI-based flow reactors are highly adaptable, easily tailored to specific reaction requirements, and economically viable, underscoring their broad potential for continuous flow organic synthesis.

Chapter 6. Conclusion

This chapter systematically concludes the design, hydrodynamics, and multifunctional applications of coiled flow inverter (CFI) reactors for sustainable CO₂ capture and continuous-flow organic synthesis. By enhancing mixing, mass transfer, and enabling real-time visualization, CFIs overcome key limitations of conventional reactors. The integration of waste-derived absorbents such as lignin and urine offers a low-cost, sustainable alternative to conventional amine systems, achieving high CO₂ removal efficiency. Additionally, the successful intensification of organic reactions highlights the broader applicability of CFIs in flow chemistry. Overall, this work establishes a scalable, eco-friendly approach that combines process intensification with waste valorization, contributing to sustainable carbon management and circular economy goals.

Publications:

1. **A. Tripathi**, K. Sarkar, S. Patel, U. Mishra, K. D. P. Nigam, D. Panda, K. G. Biswas, *Elucidating flow-directed 98% CO₂ absorption using millimeter-sized coiled flow inverters: Nanocellulose-aided sustainable scope*. **Chemical Engineering and Processing - Process Intensification**, 2024, 205, 110022
2. **A. Tripathi**, S. Patel, P. Singh, K. D. P. Nigam, K. G. Biswas, D. Panda *Fluorescence on the Flow: Continuous Xanthene Dye Synthesis from Gallic Acid in a Coiled Flow Inverter* **ChemPlusChem** 2025, e202500313
3. **A. Tripathi**, S. Kumar, S. Patel, A. Singh, D. Panda, K. G. Biswas *Turing Urine into Carbon Sink: Continuous 96% CO₂ Capture using Urea-Lignin Solution in a Coiled Flow Inverter (2026) (Communicated)*
4. A. Kumar, A. Anand, **A. Tripathi**, P. N. Singh, U. Mishra, D. Panda, K. G. Biswas *A Sustainable Route of Mass Transfer for Liquid-Liquid Flow in Millimeter-Sized Conduit: Unearthing the Potential of Agrowaste-Derived Nanomaterials*.

Waste and Biomass Valorization 2025, 17, 295–306

5. P. N. Singh, **A. Tripathi**, A. Kashyap, S. Patela, D. Panda, K. G. Biswas
Nanofluid-directed Mass Transfer Intensification in a Coiled Flow Inverter: Hydrodynamic–
Interfacial Synergy in a Liquid–Liquid System
Chemical Papers (2026) ([Under Revision](#))