EMERALD: A Novel Radial-Current Electrified Reactor for the Intensification of SMR. Modeling and Experimental Validation.

Federica Romanelli[1], Luca Cozzarolo[1], Francesco Poma[1], Matteo Ambrosetti[1], Mauro Bracconi[1], Matteo Maestri[1], Alessandra Beretta[1], Gianpiero Groppi[1], Bruna Mello-Gabbrielleschi[2], Bryce Williams[2], Enrico Tronconi[1*]

1 Laboratory of Catalysis and Catalytic Processes, Dipartimento di Energia, Politecnico di Milano, Via La Masa 34, 20156 Milan, Italy;

2 Innovation Campus Frankfurt, Air Liquide Forschung und Entwicklung GmbH, Gwinnerstraße 27-33, 60388 Frankfurt am Main, Germany

**Corresponding author: enrico.tronconi@polimi.it*

Highlights

- Electrified catalytic reactor with radial current and centrifugal gas flow.
- Geometry-driven Joule heating intrinsically matching SMR heat demand.
- Suppression of inlet cold spots and reduced pressure drop.
- Multiscale modeling and experiments on a lab-scale reactor validate the EMERALD concept.

1. Introduction

Electrification of catalytic reactors represents a promising strategy for decarbonizing energy-intensive chemical processes. Steam methane reforming (SMR), the main industrial route for hydrogen production, requires large heat inputs and typically suffers from strong thermal gradients due to the mismatch between heat supply and the local heat demand of the endothermic reaction.

To address this challenge, a novel Joule-heated electrified reactor concept (EMERALD) is proposed [1]. The design combines radial electric current with centrifugal gas flow through an annular packed foam catalytic bed. The radial geometry produces a variable cross-section for both gas and current flow, resulting in maximum heat generation at the bed entrance and a radial decay proportional to $1/r^2$. This intrinsically tailored heat generation closely matches the local heat demand of the reforming reaction, enabling improved temperature control and intensified reactor operation.

2. Methods

The EMERALD concept was investigated through a combined modeling and experimental approach. Reactor simulations were performed using a hierarchical hybrid heterogeneous modeling framework [2]. Detailed 3D CFD simulations were used to derive effective transport correlations and parameters for 1D and 2D porous-media reactor models [3].

Experimental validation was conducted in a lab-scale EMERALD reactor with a catalytic bed volume of 0.1 liters. Rh-based catalyst pellets packed in SiSiC foams acting as resistive elements were used. Temperature profiles in the radial direction were measured using multiple thermocouples, while outlet gas compositions were analyzed using an online MicroGC. An external heating tape allowed control of the reactor casing temperature.

3. Results and discussion

Modeling results presented in Figure 1 show that, under identical reference operating conditions (Rh catalyst, GHSV = 20 Nl h^{-1} $gcat^{-1}$, $H_2O:CH_4:H_2$ = 2.5:1:0, V = 21.4 l, Power = 234 kW, T_{in} = 773 K, P = 7 bar, adiabatic behavior), conventional axial Joule-heated reactors develop a pronounced cold spot at the bed inlet. In contrast, the EMERALD radial configuration largely suppresses cold spot formation. This improvement arises from the spatial distribution of Joule heating generated by the radial current flow. The heat generation rate is highest at the catalytic-bed entrance and decreases radially following a 1/r² profile, closely matching the local heat demand of the reforming reaction. The radial configuration also leads to a significant reduction in pressure drop.

Experimental results obtained in the lab-scale EMERALD reactor (Figure 2) confirm these trends under operating conditions compatible with the experimental setup (Rh catalyst, GHSV = 5 Nl h^{-1} $gcat^{-1}$, H_2O:CH_4 = 3:1, V = 0.1 l, P = 1 bar). Temperature profiles measured during operation were governed by the net heat flux (electric power minus reaction heat). Negative net heat flux resulted in monotonically increasing temperature profiles, near-adiabatic conditions produced flatter profiles, and positive net heat flux generated temperature maxima within the catalytic bed. For all operating conditions, outlet compositions approached thermodynamic equilibrium, with methane conversion increasing from 44.6% (Profile 1) to 70.8% (Profile 13).

Both simplified reactor models and detailed CFD simulations reproduced the experimental trends, validating the EMERALD concept and confirming its capability to optimize temperature profiles in electrified endothermic catalytic reactors.

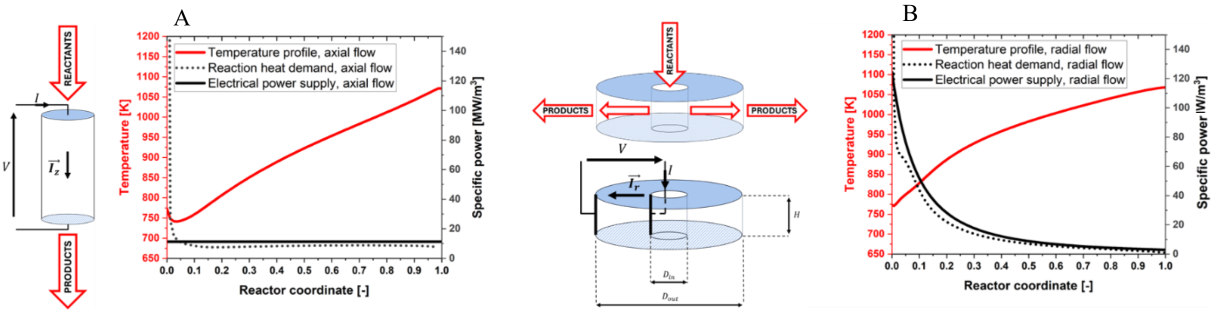

Figure 1. Comparative simulations results: axial (A) and radial (B) electrified reactor configurations.

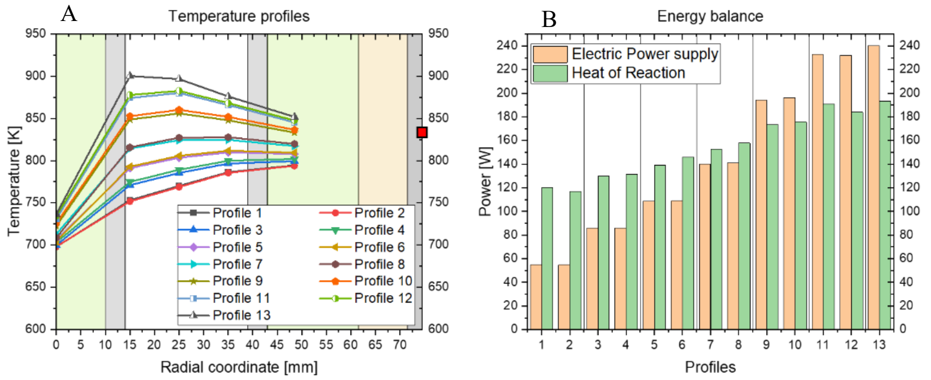

Figure 2. Experimental results on the lab-scale EMERALD reactor: temperature profiles (A) and energy balance (B)

4. Conclusions

A novel electrified reactor concept based on radial current flow and centrifugal gas flow has been developed and validated for steam methane reforming. The EMERALD configuration enables intrinsically tailored heat generation that closely matches the local heat demand of the endothermic reaction. Both modeling and experimental results demonstrate suppression of cold-spot formation, optimized temperature profiles, and conversion approaching thermodynamic equilibrium. The proposed reactor architecture provides a promising strategy for intensified electrified catalytic processes and low-carbon hydrogen production. Scale-up and optimization studies are in progress.

References

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Keywords
Electrified catalytic reactor; Process intensification; Steam methane reforming; Joule heating