Heating the Catalyst, Not the Planet: Magnetic Induction as a Platform for Electrified CO_2 and NH_3 Valorisation

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Highlights

- Volumetric catalyst heating >800 °C at ≤60 mT
- 74–78% CO_2 conversion under magnetic methanation
- >1500 mmol NH_3 gRu^{-1} h^{-1} in electrified NH_3 synthesis
- Minute-scale on/off dynamic catalytic response

1. Introduction

Decarbonisation of the chemical industry requires electrified catalytic processes compatible with intermittent renewable energy. Conventional externally heated reactors suffer from thermal inertia, slow dynamics, and inefficient heat transfer. Magnetic induction heating enables direct, volumetric energy dissipation inside ferromagnetic catalyst particles via hysteresis losses under alternating magnetic fields (AMF), offering rapid response and selective heating of active sites

Here, we present magnetic heating as a general catalytic platform for circular carbon and nitrogen chemistry, demonstrated across CO_2 methanation, reverse water–gas shift (RWGS), methanol synthesis, ammonia synthesis, ammonia decomposition, and methane decomposition. The work is framed as a proof-of-concept for electrified heterogeneous catalysis.

2. Methods

Soft-magnetic $Co_{0.67}Ni_{0.33}$ nanoparticles embedded in γ-Al_2O_3 nanosheets were synthesised via scalable co-precipitation and AlN hydrolysis, forming high-surface-area nanocomposites (~140 m^2 g^{-1}). The materials exhibited saturation magnetisation up to 50 emu g^{-1} and heating capability exceeding 800 °C at AMF amplitudes below 60 mT.[1]

Catalytic experiments were conducted in custom-designed fixed-bed induction reactors (234 kHz, up to 80 mT). CO_2 hydrogenation was studied between 210–300 °C and 0–20 barg, while ammonia synthesis was evaluated at 5.5 MPa under dynamic magnetic switching.[2] Ammonia decomposition was investigated at 400 °C with minute-scale response times.[3] Microkinetic modelling and DFT calculations were employed to elucidate reaction pathways and rate-determining steps.

3. Results and discussion

Magnetic Heating Performance

The $CoxNi_{1-x}$–Al_2O_3 nanocomposites achieved rapid volumetric heating exceeding 700–800 °C within minutes under moderate magnetic fields, confirming suitability for high-temperature catalytic applications while maintaining magnetic stability under reductive atmospheres (Figure 1).[1]

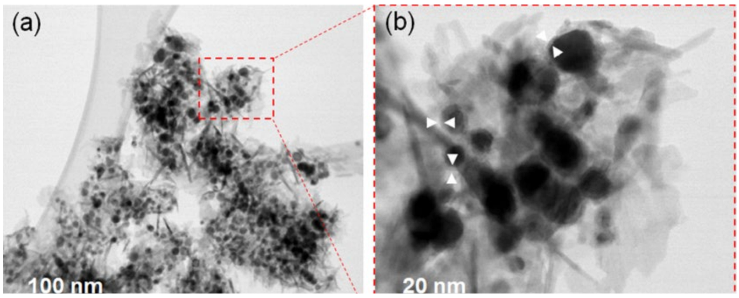

Figure 1: Bright-field STEM micrographs ((a), (b)) of the magnetic nanocomposite C67N33-A70. The arrows in panel (b) indicate the presence of a surface oxide layer surrounding the $Co_{0.67}Ni_{0.33}$ nanoparticle.

CO_2 Valorisation

Under magnetic heating, CO_2 methanation achieved up to 74–78% conversion at 300 °C and 20 barg with excellent 130 h stability. Conversion correlated linearly with accessible metal sites. Microkinetic modelling (14 elementary steps) identified COOH* dissociation and CH_3* hydrogenation as key rate-controlling steps. The adsorption-energy landscape obtained from DFT rationalised selectivity trends between methane, CO (RWGS), and methanol pathways, with methane favoured due to weak CH_4 adsorption (−0.25 eV).

Methane Decomposition (Electrified CDM)

Magnetically heated commercial Fe–Ni–Co alloys achieved methane conversions above 40% at 650 °C. Carbon nanotubes formed via a tip-growth mechanism, confirming the compatibility of magnetic induction heating with carbon-forming reactions. The catalytic performance depended strongly on alloy composition and operating temperature, which also influenced the nature and structure of the deposited carbon species.[4]

Ammonia Synthesis and Decomposition

Ba-promoted Ru/CN-A catalysts achieved >1500 mmol $NH_3\ gRu^{-1}\ h^{-1}$ at 350 °C and 5.5 MPa under magnetic heating. Dynamic on/off switching enabled full start-up within <10 min and rapid shutdown. Ammonia decomposition exhibited rates of 5.33 $molNH_3\ gRu^{-1}\ h^{-1}$ at 400 °C with minute-scale, allowing tunable H_2/NH_3 output ratios.[2]

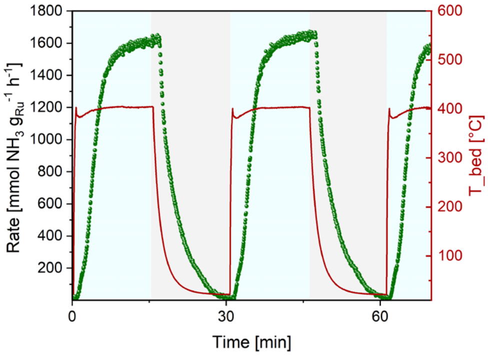

Figure 2: Magnetically driven dynamic ammonia synthesis over Ba–Ru. Two switching cycles shown.

4. Conclusions

Magnetic induction heating was demonstrated as an enabling strategy for **electrified heterogeneous catalysis** in circular carbon and nitrogen chemistries. By decoupling catalyst heating from the reactor walls and depositing energy directly into ferromagnetic nanocomposites, the system enables **rapid start-up, dynamic operation**, and efficient thermal management under reductive reaction conditions. Stable, high catalytic performance was achieved in CO_2 methanation, methane decomposition, ammonia synthesis, and ammonia decomposition, supported by microkinetic modelling and DFT analysis that elucidated the governing elementary steps. The combination of **volumetric heating, structural stability, and dynamic responsiveness** highlights the potential of magnetically heated reactors as **modular platforms compatible with intermittent renewable electricity**. This proof of concept establishes magnetic catalysis as a viable pathway towards **scalable, low-carbon, and dynamically operated chemical manufacturing**.

References

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Keywords

Magnetic induction heating; CO_2 valorisation; Ammonia synthesis; Electrified catalysis