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Research Article

Graphite Felt-Sandwiched Ni/SiC Catalysts for the Induction Versus Joule-Heated Sabatier Reaction: Assessing the Catalyst Temperature at the Nanoscale

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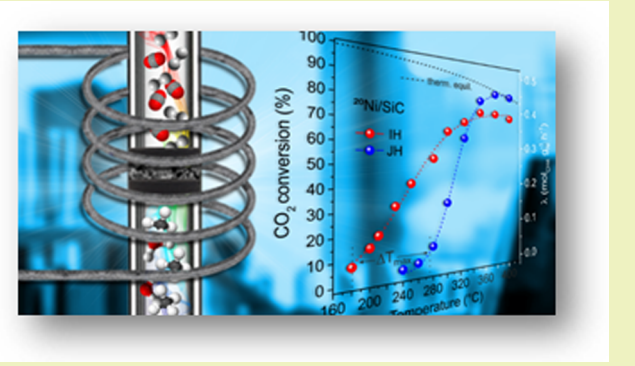
ABSTRACT: The paper describes a series of graphite felt-sandwiched ^{k}Ni/SiC composites at variable metal loading (k = 10, 15, and 20 wt %) and their application as catalysts for the CO_2 methanation process (Sabatier reaction) under two distinct and conceptually different heating setups: Joule heating versus induction heating (IH). A comparative analysis carried out on all catalysts from this series operated under the two heating configurations has unveiled the superior performance of radiofrequency (RF)-heated (IH) catalysts in the process. Most importantly, it has offered a practical tool to map the gap existing between the macroscopic temperature value measured at the catalyst bed using a remote-sensing thermometer (pyrometer) and that (real) of the excited metal nano-objects (Ni NPs) directly engaged in the RF-heated catalytic process. Besides the evident advantages of IH technology applied to the methanation process in terms of process rates (λ) already under nominally low reaction temperatures, the virtual absence of any thermal inertia and the subsequent fast modulation of the temperature at the catalytic bed demonstrates unique features of this heating technology in terms of process safety (cold-reactor walls) and reduction of energy wastes (neither pre- and postcatalyst heating of reagents and products nor that of the whole reactor volume and its peripheral walls).



KEYWORDS: *induction heating, methanation reaction, Joule heating, temperature of inductively heated nano-objects, SiC-based catalysts*

INTRODUCTION

The development of integrated chemical strategies for the energy conversion and storage is a key priority of our modern society to address a truly renewable energy-based transition.[1] In the power-to-gas (P2G) chain, the exceeding amount of electrical energy produced from renewable and CO_2-free energy suppliers (i.e., wind, hydraulic, and solar) is converted into H_2 via water electrolysis. If not immediately used, H_2 can be employed as a reagent in CO_2 hydrogenation (Sabatier or methanation process)[2−5] to give synthetic natural gas (SNG; CH_4). SNG is an energy vector of more practical use/management/distribution within the existing infrastructures and gas grids. Storage and transport conditions for methane are also easier and cheaper compared to those required for hydrogen.

CO_2 methanation is a highly exothermic process (ΔH^0 = −165 kJ mol^{-1}); nevertheless, it requires the use of catalysts along with large external heat input to overcome the severe kinetic limitations linked to CO_2 chemical inertness.[6] External heating implies larger energy cost burdening on the process. In addition, its combination with the reaction exothermicity and the thermal inertia of classically Joule-heated (JH) reactors hampers an accurate temperature control at the catalytic bed where local temperature gradients (hot spots) can be formed. The latter are typical sources of serious drawbacks and technical limitations linked to the catalyst stability and its performance on long-term runs other than representing a primary energy waste for the process.

In recent years, new achievements in catalysis have mainly pointed out on the process intensification[7] by guaranteeing a quantum leap in its efficiency in terms of time, energy costs, employment of noncritical raw materials, and environmental impact rather than squeezing few percentages on the yield and selectivity of consolidated protocols of the state of the art. The electromagnetic induction heating (IH) or radiofrequency

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(RF) heating of electrically conductive or magnetic susceptors has already been exploited for a wide range of targeted applications, spanning from biomedical area[8,9] in the treatment of diseases (through magnetic hyperthermia)[10] to that of processes for metallurgic manufacturing.[11] Only recently, this technology has been exploited in catalysis,[12] spotting light on the unique potentiality of this "noncontact" technology for the heat management in highly exo- and endothermic processes.[12] The possibility to convey heat only where it is needed for the chemical process using magnetically or electrically conductive susceptors/catalysts has been used to overcome several heat transfer limitations occurring in classical (Joule) heating schemes. IH indeed limits energy wastes associated to undesired and detrimental heating paths[12,13] and drastically reduces the thermal inertia (heating/cooling rate) at the catalytic bed.[12]

As far as the CO_2 methanation reaction is concerned, IH has successfully been exploited by means of magnetic nanoparticles (NPs) and/or core−shell systems joining high hyperthermic efficiency[14−16] to excellent catalytic performance. Similarly, electrically conductive susceptors decorated with catalytically active NPs have been employed as robust catalytic systems to run CO_2 hydrogenation under severe and dynamic conditions.[12] We have recently described an RF-heated methanation scheme based on highly Ni-loaded/γ-Al_2O_3 (up to 40 wt %) composites as electrically conductive and magnetic susceptor/catalysts for rational heat management at the catalytic bed and with a drastic reduction in the nominal temperature values needed to efficiently perform the process [CO_2 conversion (X_{CO_2}) up to 98% with methane selectivity (S_{CH_4}) > 99% already at operative temperatures of 210−230 °C].[13] Pieces of evidence from this study have led us to conclude that the catalyst temperature measured at the catalytic bed using a remote-sensing thermometer (pyrometer; ø laser beam: ≈ 500 μm, power < 1 mW) is an average value between that of the support (γ-Al_2O_3) and that of the RF-excited nickel particles decorating its surface (catalytic sites). These results, together with others related from the literature,[17,18] support the idea of a temperature gap between the value measured by the laser spot (macroscopic) and that (real) of the heated nano-objects (Ni NPs). Anyhow, the precise determination of the entity of this gap and thus the temperature value at the nanoscale remains a challenging task to be addressed,[14,19−21] particularly in continuous flow, fixed-bed reactors operated under relatively harsh experimental conditions. Current technologies applied to this challenging task are generally based on the development and use of thermosensitive molecules as molecular temperature probes[19] as well as advanced spectroscopic techniques as diagnostic tools for the determination of the local temperature values.[21]

This paper describes the design and synthesis of a new family of graphite felt (GF)-sandwiched ^{k}Ni/SiC composites with variable metal loading (k = 10, 15, and 20 wt %) as catalysts/susceptors for the methanation process to be operated under two distinct heating technologies: Joule heating (JH) versus IH. The choice of nickel as a metal active site is based on its renewed catalytic activity and stability in the process. Moreover, its magnetic properties make it a useful susceptor to run the process under IH conditions. SiC is a semiconductor, nonoxide ceramic featured by good thermal conductivity but not suitable to convert electromagnetic energy into heat (not RF-heatable).[22] To improve the hyperthermic efficiency of the catalytic system, Ni/SiC was sandwiched between two electrically conductive and IH-responsive (eddy or Foucault currents) GF disks. The comparative analysis of these catalytic materials under different heating configurations (JH vs IH) and experimental conditions [reaction temperature and gas hourly space velocity (GHSV)] has provided a practical tool for mapping the temperature gap existing between the macroscopic value measured at the catalyst bed using the pyrometer and that (real) of the excited metal nano-objects (Ni NPs) directly engaged in the RF-heated catalytic process.

At the same time, the catalytic study under IH has pointed out the superior performance of catalysts operated with this direct and noncontact heating technology together with its key advantages in terms of process safety (cold-reactor walls) and reduction of energy wastes.

EXPERIMENTAL SECTION

Materials and Methods. Silicon carbide (SiC) was purchased from Sicat SARL (www.sicatcatalyst.com) as mesoporous pellets (3 × 1 mm, h × ø)[23−25] with a specific surface area (SSA) measured by a N_2 physisorption (at 77 K) of 27 ± 3 m^2 g^{-1}. SiC pellets were thoroughly washed with distilled water and oven-dried for several hours at 140 °C to remove all powdery fractions prior to be employed as supports for the preparation of the Ni-based composites. Unless otherwise stated, all other reagents and solvents were used as received by the providers without any specific purification/treatment.

Synthesis of ^{k}Ni/SiC Composites. In a typical procedure, SiC pellets (8 g) were impregnated with a proper amount (3.0, 4.8, and 6.8 mL) of a 5 M aqueous $Ni(NO_3)_2{\cdot}6H_2O$ solution to get ^{k}Ni/SiC with a theoretical metal charge of k = 10, 15, and 20 wt %, respectively. Impregnated samples were evaporated and oven-dried at 110 °C for 2 h before being calcined in air at 350 °C for 2 h as to prepare the corresponding metal oxides. The as-obtained ^{k}NiO/SiC precatalysts (k = 10, 15, and 20 wt %) underwent reduction treatment under a pure H_2 flow (100 mL min^{-1}) at 350 °C for 2 h. This reduction step was accomplished as an in situ precatalyst treatment whatever may be the nature of the heating setup (JH or IH) employed for the CO_2 methanation trials. Scanning electron microscopy (SEM) was carried out on a ZEISS 2600F instrument with a resolution of 5 nm. A 10 kV electron beam was used for SEM imaging operated in the high vacuum mode, using BSE and SE detectors. For measurements, samples were deposited onto a double-face graphite tape holder as to avoid the charging effect during the analysis. Transmission electron microscopy (TEM) was carried out on a JEOL 2100F working at 200 kV accelerated voltage, equipped with a probe corrector for spherical aberrations, and a point-to-point resolution of 0.2 nm. Elemental mapping was finally accomplished by scanning transmission electron microscopy (STEM) on a JEOL 2100F electron microscope equipped with a Gatan Energy Filter and cold field-emission gun operated at 200 kV with 1.5 Å lattice resolution. For these measurements, samples were dispersed by ultrasound treatment (5 min) in an ethanol solution and a drop of each suspension was deposited on a copper grid covered with a holey carbon membrane for observation. Powder X-ray diffraction (PXRD) measurements were carried out on a D8 ADVANCE Bruker diffractometer with a Cu Kα X-ray source (λ = 1.5406 Å). Rietveld refinements are performed using GSAS-II software.[26] The mean size of ordered (crystalline) domains (τ) is calculated from the Debye−Scherrer equation: $\tau = K\lambda/\beta \cos\theta$, where K is a shape factor, λ is the X-ray wavelength, β is the line broadening at half the maximum intensity (fwhm), and θ is the Bragg angle. The Brunauer−Emmett−Teller (BET) SSAs were calculated from N_2 physisorption isotherms recorded at 77 K on an ASAP 2020 Micromeritics instrument. Pore size distribution was determined by the Barrett−Joyner−Halenda (BJH) method applied to the desorption isotherm branches. Each sample was degassed/activated at 250 °C under vacuum for 8 h in order to desorb moisture and adsorbed species on its surface. Thermogravimetric analyses

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ACS Sustainable Chem. Eng. XXXX, XXX, XXX−XXX

(TGAs) were run under air (100 mL min^{-1}) on a TGA Q5000 thermogravimetric analyzer (TG/DTA) using a heating rate of 10 °C/min. The average weight measured for each sample was maintained around 10 mg maximum. Inductively coupled plasma optical emission spectrophotometry (ICP-OES) measurements on mineralized ^{k}NiO/SiC precatalysts were accomplished on a Varian 720 ES ICP-OES instrument. The IH setup (EasyHeat 8310, 4.2 kW, Ambrell Ltd) is made of a six-turn spiral induction coil (length = 1.05 m, pure coil resistance = 2.066 × 10^{-3} Ω), cooled by means of an external chiller containing water/glycerol (10%, v/v) as the cooling mixture. For the temperature measurement in a typical RF-heated (IH) experiment, temperature at the catalyst bed was monitored/controlled/regulated in almost real-time using a PID system (proportional integral derivative controller, Eurotherm model 3504) connected to a laser pyrometer (Optris, ø laser beam: ≈500 μm, power < 1 mW, located at ≈ 15 cm from the catalyst and working in the 150−1000 °C range with an accuracy ±1 °C), shot up on the catalyst/susceptor. A standard calibration procedure[27] has been used to fix the emissivity factor for each ^{k}Ni/SiC (k = 10, 15, and 20 wt %) catalyst of the study. The heating/cooling rate allowed for the system was about 60−80 °C min^{-1} in the 150−300 °C temperature range. The inductor frequency was constantly maintained at 265 ± 5 kHz, while the current flowing through the induction coils varied from 200 to 450 A.

IH Setup. In a typical experiment, the quartz reactor containing the catalyst was housed inside the coils of the induction heater and temperature real-time control/regulation was ensured using a PID system (proportional integral derivative controller, Eurotherm model 3504) connected to a laser pyrometer (remote-sensing thermometer) shot up on the catalyst bed (see Figure 3 for the sake of clarity).

JH Setup (Electrical Oven). In a typical experiment, the quartz reactor containing the catalyst was housed in an electrical oven (ERALY Co., $ø_{OD}$ = 200 mm; $ø_{ID}$ = 55 mm; depth: 300 mm; I_{max} = 8.6 A, and T_{max} = 1100 °C). The temperature of the system was monitored using two type-K thermocouples, one for regulating the oven temperature (T_F) and an additional one located in close contact with the catalytic bed (T_C) for measuring the temperature swings throughout the process. For these trials, we used thermocouples of $ø_{ED}$. 0.5 mm, very close to the dimension of the laser pyrometer spot in IH. Before each catalytic run, the catalyst was allowed to reach and stabilize (30−45 min) at the target temperature under a pure stream of He (max temperature deviation recorded between T_F (F = furnace) and T_C (C = catalyst) after stabilization = ±3 °C) (see Figure 3 for the sake of clarity).

Catalytic Tests. The CO_2 methanation reaction (eq 1) was conducted at atmospheric pressure in a fixed-bed quartz tubular reactor ($ø_{ID}$ = 12 mm and length = 400 mm) charged with 0.6 g of the ^{k}Ni/SiC catalyst (k = 10, 15, and 20 wt %; $V \approx 0.8$ cm^3) and housed on the proper heating setup (EasyHeat 8310 IH setup or a classical external furnace).

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \qquad \Delta H = -165 \text{ kJ mol}^{-1} \qquad (1)$$

In a typical catalytic run, a H_2/CO_2 gas mixture (4 v/v) at variable GHSVs obtained by a series of calibrated mass flow controllers (Brookhorst) was continuously fed through the catalytic bed maintained at the target temperature. Gases at the reactor outlet are passed through a trap filled with silicon carbide pellets where water is condensed before reaching the gas chromatograph for analysis. Reactants and products were analyzed online at the respective reactor outlets using an R3000 (SRA Instrument) micro-gas chromatograph (μGC) equipped with an MS5A column for H_2, CH_4, and CO detection and a PPU column for CO_2 and C_2 detection with a thermal conductivity detector (TCD). All reactors exit lines were maintained at 110 °C by external heating tapes as to avoid water condensation in the feed.

CO_2 conversion (X_{CO_2}) and CH_4 selectivity (S_{CH_4}) were calculated according to the following equations (eqs 2 and 3)

$$X_{CO_2}\,(\%) = \frac{F_{CO_2(in)} - F_{CO_2(out)}}{F_{CO_2(in)}} \times 100 \qquad (2)$$

$$S_{CH_4}\,(\%) = \frac{F_{CH_4(out)}}{F_{CH_4(out)} - F_{CO(out)}} \times 100 \qquad (3)$$

where $F_{i(in/out)}$ (mL min^{-1}) is the flow rate of each component in the gas feed at the reactor inlet or outlet.

RESULTS AND DISCUSSION

Synthesis and Characterization of ^{k}Ni/SiC Catalysts (k = 10, 15, and 20 wt %). ^{k}Ni/SiC composites (k = 10, 15, or 20 wt %) were straightforwardly prepared using a wet impregnation technique followed by conventional thermal calcination/reduction steps (see the Experimental Section for procedure details). The impregnated solids were oven-dried at 110 °C for 2 h and calcined in air at 350 °C for additional 2 h as to convert the nickel nitrate into its corresponding oxide. Catalysts were further reduced under a hydrogen flow (100 mL min^{-1}) at 350 °C for 2 h. All composites from this series were thoroughly characterized by PXRD, TEM/STEM, and N_2-physisorption analyses, while their effective metal loading was determined (on NiO precatalysts) through ICP-OES measurements.

The catalyst composition and the average Ni NP size before and after the NiO reduction were systematically analyzed through PXRD. Figure 1 shows the PXRD patterns recorded

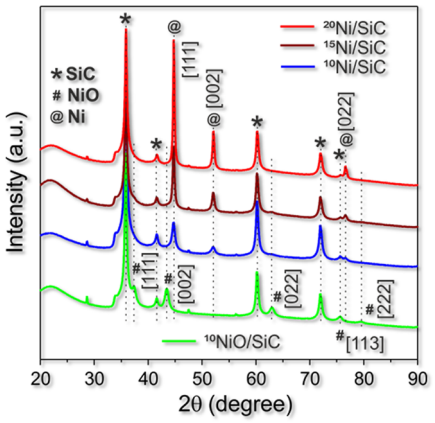

Figure 1. PXRD profiles of ^{10}NiO/SiC and ^{k}Ni/SiC (k = 10, 15, and 20 wt %) for comparison.

for the three ^{k}Ni/SiC (k = 10, 15, and 20 wt %) samples in comparison with the model system ^{10}NiO/SiC, arbitrarily selected as a representative precatalytic system from this series. Hydrogenation (H_2 flow: 100 mL min^{-1}, at 350 °C for 2 h) of all calcinated precatalysts provides a complete NiO conversion into the corresponding Ni^0 particles. NiO diffraction peaks (at 2θ = 37.3, 43.4, 63.0, 75.6, and 79.6°, respectively)[28] are almost quantitatively suppressed in all reduced samples, while new distinctive peaks ascribed to Ni^0 appear at 2θ = 44.5, 51.8, and 76.3°.[29] Expectedly, the peak intensity of the latter grows up appreciably when passing from 10 to 20 wt % of metal loading in the SiC normalized spectra. Notably, the chemical inertness of the SiC carrier is likely at the origin of the pure Ni^0 phases obtained in all samples after the reduction step. The absence of strong chemical interactions between the metallic phase and the nonoxide ceramic support is witnessed by the absence of hardly reducible forms[22] at the interface, resistant to

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ACS Sustainable Chem. Eng. XXXX, XXX, XXX−XXX

the relatively mild reduction conditions used. The Ni particle size was roughly estimated using the Scherrer equation[30] applied to the peak fwhm of diffraction peaks at 2θ = 44.5 and 51.8°. The mean values measured for the ^{k}Ni/SiC samples were fixed to 13 ± 1, 21 ± 2, and 26 ± 2 nm for k = 10, 15, and 20 wt %, respectively.

The higher the metal loading, the higher is the mean nickel particle size and the generation of larger metal aggregates. While Ni/SiC composites at relatively low Ni contents (i.e., ^{10}Ni/SiC) can boast a higher stability extent due to the presence of amorphous SiO_2/SiO_xC_y layers at the carrier topmost surface that contribute to stabilize and disperse the metal active phase,[22,31] higher metal loadings and larger metal aggregates on supports with moderate SSA are less leaching-resistant. As an example, SEM images of the ^{20}Ni/SiC catalyst (Figure S1) at different magnifications unveil the almost complete coating of the SiC carrier with nickel superstructures and structural vacancies; the latter are probably originated by the partial removal of poorly stabilized nickel aggregates. Therefore, the higher the metal content used in the catalysts' preparation, the higher the deviation between the theoretical and the effective metal loading in the composites. This trend was confirmed by the ICP-OES analysis on the final catalysts. While the ^{10}Ni/SiC sample showed an excellent match between the theoretical and the measured nickel loading (9.3 ± 0.3 wt %), ^{20}Ni/SiC displayed a higher deviation from the theoretical content (17.0 ± 0.8 wt %) (Table 1). At odds with

Table 1. ICP-OES Analysis, SSA, Pore Volume, and Pore Size Distribution Measured on Each ^{k}Ni/SiC (k = 10, 15, and 20 wt %) Composite in Comparison with the Bare Ceramic Support

entry	sample	Ni wt % (ICP-OES)	SSA[a] ($m^2\ g^{-1}$)	total pore volume[b] ($cm^3\ g^{-1}$)	average pore size[c] (nm)
1	SiC		27	0.16	23.8
2	^{10}Ni/SiC	9.3 ± 0.3	29	0.14	17.6
3	^{15}Ni/SiC	14.0 ± 0.5	26	0.13	21.6
4	^{20}Ni/SiC	17.0 ± 0.8	24	0.13	22.6

[a]BET SSA measured at T = 77 K. [b]Total pore volume determined using the adsorption branch of the N_2 isotherm at P/P_0 = 0.98. [c]Determined by BJH desorption average pore width ($4V/A$).

XRD data, XPS surface analyses of all Ni/SiC composites unveiled the presence of NiO_x forms (Figure S2A,B)[32] resulting from a rapid passivation of metal deposits during the sample handling in air and their manipulation for analysis (formation of thin metal-oxide layers). For this reason, each NiO/SiC precatalyst underwent H_2 flow reduction at 350 °C in situ (see the Experimental Section) just prior of its exposure to the reagents' mixture for catalysis. The SSA, the total pore volume, and the mean pore size measured for all Ni composites (Table 1, entries 2−4 and Figure S3B−D) were very similar and close to the morphological parameters recorded for the bare SiC support (Table 1, entry 1 and Figure S3A). All samples present classical type-II isothermal profiles and moderate SSA values. The meso−macroporous nature of the ceramic carrier was moderately affected by the deposition of Ni NPs and by the final metal loading in the composite. Although any conclusion based on these moderate morphological deviations remains speculative and poorly significant to the manuscript purposes, it can be simply claimed that the higher the metal charge, the lower is the SSA value of the composite.

TEM on ^{k}Ni/SiC (Figure 2A,B for k = 10 and Figure 2D,E for k = 15 wt %) showed a relatively homogeneous dispersion of metal NPs all over the SiC support. Moreover, a statistical analysis of NP size distribution carried out on each catalyst (Figure 2C,F) was in good agreement with PXRD outcomes. High-resolution (HR) TEM analysis (Figure S4) on ^{10}Ni/SiC has finally revealed the presence of crystalline phases featured by distinctive interplanar distances of 0.21 and 0.24 nm, characteristic of the (1 1 1) planes of Ni[33] and SiC[34] phases, respectively.

Methanation Reaction with ^{k}Ni/SiC as a Catalyst under Two Heating Configurations: JH Versus IH. Looking for more efficient and energy-saving approaches to the methanation reaction, the ^{k}Ni/SiC (k = 10, 15, and 20 wt %) catalysts were investigated under two different reactor configurations: (i) a classical reactor scheme (Figure 3A) using an electrical furnace for the catalyst heating through convection, conduction, and/or radiation heat transfer (named hereafter as Joule-heating mode; JH) or (ii) an IH setup (Figure 3C) based on the electromagnetic properties of a susceptible medium (susceptor) exposed to a varying magnetic field (H) and its ability to convert the electromagnetic energy into heat at the catalytic bed or neighboring it (named hereafter induction-heating mode; IH).

For both reactors, temperature values were registered at the respective macroscopic heating sources. Therefore, for a JH system (Figure 3A), the temperature was monitored using two thermocouples housed in the furnace (temperature of the furnace, T_F) and in close contact with the quartz reactor (temperature of the catalyst, T_C), respectively. For the RF-heated setup (Figure 3C), the temperature was measured using a remote-sensing thermometer (pyrometer) with its laser beam directly shot over the GF susceptor (see the Experimental Section and Section 3.4 for details).

Whatever may be the heating configuration employed, ^{k}Ni/SiC powders were sandwiched in the quartz reactor between two GF disks (Figure 3B). The latter were innocent, porous, and thermal conductor supports for the catalytic material when the reaction was operated under the JH configuration (Figure 3A), whereas they exhibited the role of susceptors for the electromagnetic energy conversion into heat when the reaction was carried out under IH (Figure 3C; also see Section 3.4 for details). Blank tests carried out using the GF alone did not show any CO_2 methanation activity in the range of operational temperatures.

Effect of the Reaction Temperature and Heat Management Setup (JH vs IH) on the Methanation Performance. In a first set of experiments, we studied the effect of the reaction temperature at the catalyst bed on its performance using both heating configurations (JH vs IH), while maintaining the amount of catalyst (600 mg) and the reagent GHSV (10,000 mL $g^{-1}\ h^{-1}$) constant. As Figure 4 shows, catalysis under JH (blue -●-) presented classical sigmoidal trends for CO_2 (X_{CO_2}) conversion into SNG, whatever may be the catalytic system at work (^{k}Ni/SiC, k = 10, 15, and 20 wt %). Although ^{10}Ni/SiC reached the higher CO_2 conversion (X_{CO_2}) at 350 °C (and kept it almost unchanged in the 350−375 °C range), ^{15}Ni/SiC and ^{20}Ni/SiC showed their higher performance at 375 °C. As expected, the higher the nickel loading, the higher is the X_{CO_2}, although the

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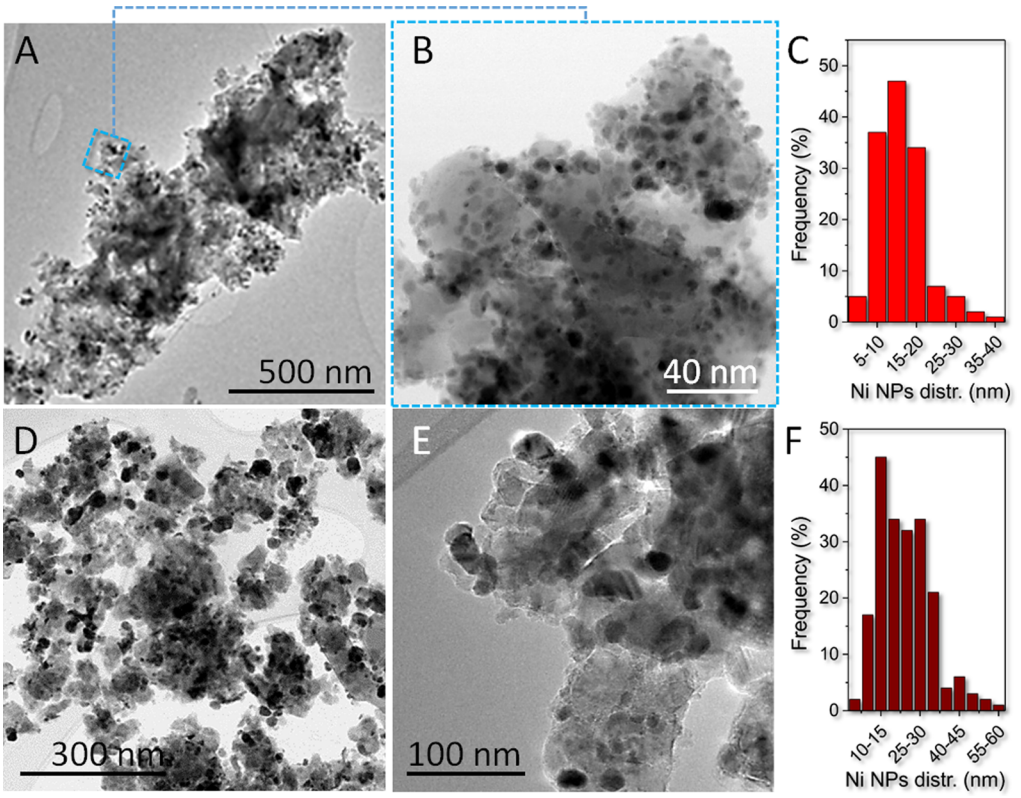

Figure 2. TEM images recorded on ^{10}Ni/SiC (A,B) and ^{15}Ni/SiC (D,E) at different magnifications along with the statistical distribution of NP sizes determined over 100 metal particles for each sample. (C,F) Ni NP size distribution on ^{10}Ni/SiC and ^{15}Ni/SiC, respectively.

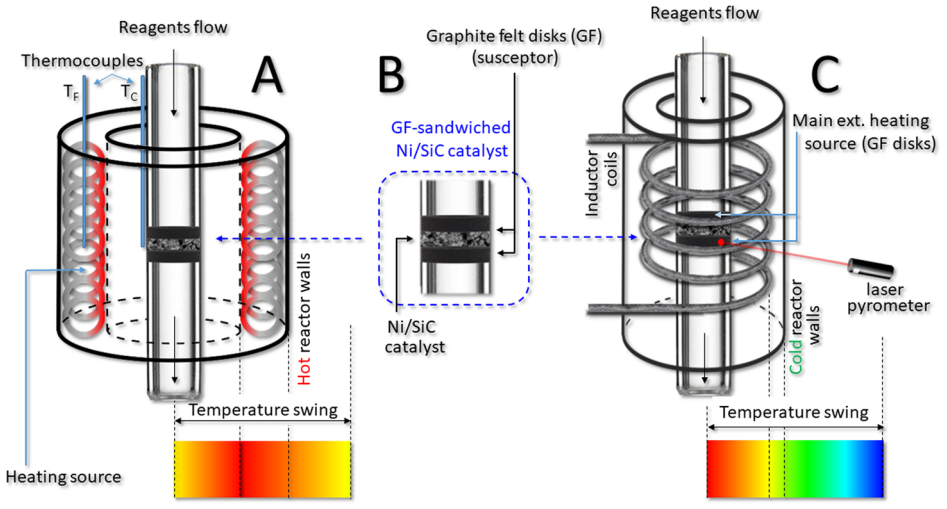

Figure 3. Representation of the adopted reactor configurations to carry out the methanation process; (A) electrical furnace (hot-wall reactor) operating with a classical JH scheme based on heat convection, conduction, and radiation; (B) details of the ^{k}Ni/SiC catalyst sandwiched between two GF disks (susceptors) and housed in the quartz tube reactor; and (C) inductor coil for the RF heating of a susceptible medium (GF, susceptor) exposed to an external varying magnetic field (H). Thermal spectra reported below each reactor configuration account for the classical temperature diffusion (to and from the catalyst) depending on the operating heating technology (JH or contact and IH or contactless).

specific catalyst rate (λ) expressed as mol_{CH_4} produced per g_{Ni} per h was superior with ^{10}Ni/SiC (see Table S1).

Under these operative temperatures (<400 °C) and irrespective of the employed heating setup, the SNG process selectivity laid constantly close to 100% with no traces of CO or other byproducts detected at the reactors' outlet. The remarkably high S_{CH_4} was partially due to the thermal conductivity of the SiC carrier[22] that was thought to mitigate the generation of local temperature gradients (hot spots) by diffusing extra heat to the whole catalyst volume[35] and ultimately favoring its removal by the action of the gaseous reagent stream (solid−gas heat exchange).

Such a heat exchange was even more efficient in a RF-heated catalyst because of the absence of reagents flow preheating until they came in contact with the (hot) catalyst surface.

When CO_2 methanation was carried out under IH (red -●-), we observed an appreciably higher catalyst performance

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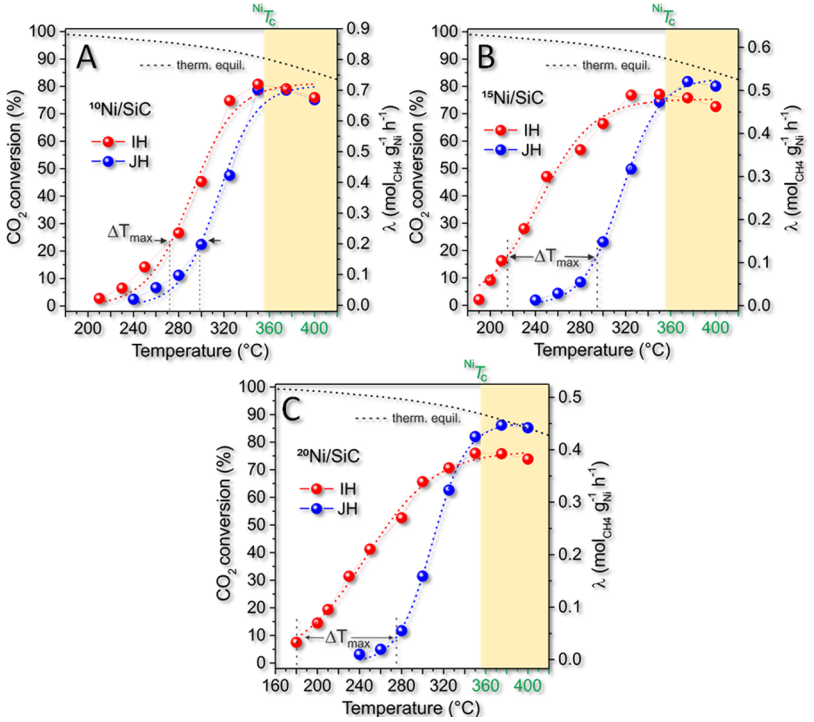

Figure 4. CO_2 methanation with ^{k}Ni/SiC [k = 10 (A), 15 (B), and 20 wt % (C)] as a function of the reaction temperature. All catalysts were tested without any thermic diluent. Reaction conditions: catalyst weight = 600 mg, GHSV (STP) = 10,000 mL g^{-1} h^{-1}, [CO_2] = 20 vol %, [H_2] = 80 vol %, H_2-to-CO_2 ratio = 4, total flow rate = 100 mL min^{-1}, atmospheric pressure. Red (-●-) and blue (-●-) curves refer to the X_{CO_2} vs temperature as experimentally determined within an IH and JH setup, respectively. CH_4 selectivity (S_{CH_4}, not shown in figures) was constantly equal to 100% in the whole temperature range. Thermodynamic equilibrium conversion (dashed black line "-----") has been included for the sake of comparison. All experimental data have been fitted with sigmoidal logistic functions of type I.

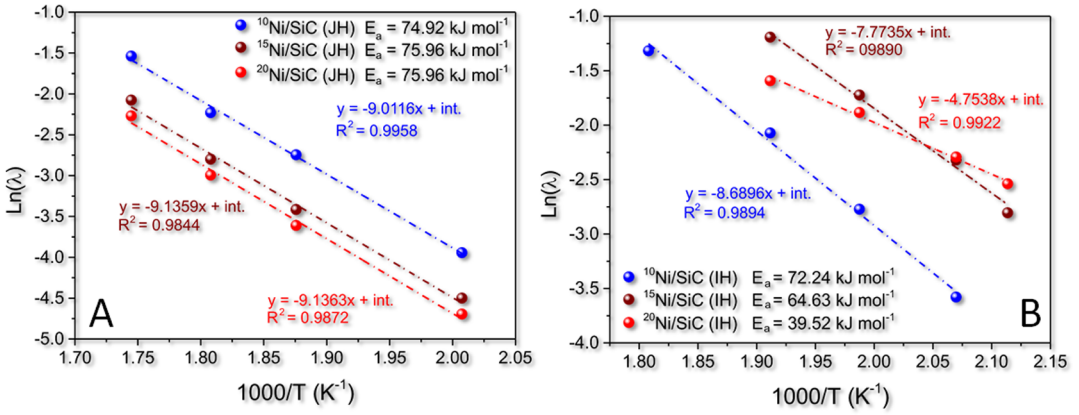

Figure 5. Arrhenius plots of ^{k}Ni/SiC (k = 10, 15, and 20 wt %) in CO_2 methanation under the classical JH (A) or IH (B) setup. λ is expressed as mol$_{CH_4}$ g$_{Ni}^{-1}$ h^{-1} and measured in the temperature range where X_{CO_2} reaches 30% conversion maximum.

already for temperatures below 350 °C, whatever may be the metal loading of the catalyst at work. Remarkably, X_{CO_2} measured at 280 and 300 °C with ^{15}Ni/SiC was up to 48 and 43% higher than that measured under the same experimental conditions but for catalysts operated under the JH mode (Figure 4B). As a result, higher productivity values (λ) were recorded for the RF-heated ^{15}Ni/SiC already at nominal low temperature (280 °C) values (Table S1). This result is of great relevance particularly in light of an industrial exploitation of these catalysts in combination with IH technology. The higher catalyst specific rate (λ) measured at low reaction temperatures with the RF-heated ^{15}Ni/SiC fulfils at least three key prerequisites of a sustainable methanation scheme: (i) catalysts with a relatively low loading of a highly dispersed and noncritical metal active phase; (ii) relatively mild operative temperatures to get high X_{CO_2} values chemoselectively into SNG; and (iii) a safer and really energy-saving reactor configuration for the heat management at the catalytic bed.

It should be stressed that Ni composites at higher metal loading (i.e., ^{15}Ni/SiC and ^{20}Ni/SiC) deviate appreciably from the classical sigmoidal profile when catalysis was operated under IH. Such a behavior was ascribed to a more complex heat management at the catalytic bed in the case of RF-heated

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ACS Sustainable Chem. Eng. XXXX, XXX, XXX−XXX

Table 2. Nickel Particle Size in the Three ^{k}Ni/SiC (k = 10, 15, and 20 wt %) and Activation Energy Values (E_a) Calculated for the CO_2 Methanation Reaction Carried Out under JH or IH from the Respective Arrhenius Plots

entry	sample	Ni NPs ø (nm)[a]	E_a (JH)[b] (kJ mol^{-1})	E_a (IH)[b] (kJ mol^{-1})	ΔE_a (JH − IH) (kJ mol^{-1})	ΔT_{max} (°C)[c]	M_s (emu/g)[d]
1	^{10}Ni/SiC	13 ± 1	75.0	72.2	2.8	26 ± 3	47.5 ± 0.7
2	^{15}Ni/SiC	21 ± 2	76.0	64.6	11.4	81 ± 4	51.2 ± 0.6
3	^{20}Ni/SiC	26 ± 2	76.0	39.5	36.5	95 ± 4	52.4 ± 0.4

[a]Determined by XRD from the Scherrer equation and the peak fwhm of the diffraction peaks at 2θ = 44.5 and 51.8°. [b]Calculated from the curves' slopes of Arrhenius plots in the temperature range where X_{CO_2} reaches 30% conversion maximum. [c]Determined as the maximum difference on the x-axis (ΔT, °C) of curves in Figure 4A,C between two points at the same CO_2 conversion (X_{CO_2} on JH and IH curves) as the maximum ΔT value (ΔT_{max}) between the GF temperature (bulk temperature) and that effectively reached at the excited metal catalyst particle sites. [d]Specific saturation magnetization (M_s) determined for the different Ni particle sizes on the basis of eq 4 and assuming a mean NiO layer of 0.5 nm in accordance with the TEM analysis on the samples of this study.

catalysts. Indeed, contributions to the catalyst heating derive in part from the inductively heated GF disks (heat transfer by convection/conduction to the thermally conductive SiC support), in part from dissipation paths related to the electrically conductive and magnetic nature of the large-sized Ni NPs (i.e., Eddy currents or Foucault currents and/or heat supplied via hysteresis losses).[12] As a proof of evidence, lower X_{CO_2} and λ values measured under IH for temperatures higher than 350 °C (Figure 4B,C) can be reasonably attributed to the loss of one heat dissipation path (e.g., heat hysteresis) as a function of the temperature effect on the metal magnetic properties (vide infra Section 3.4 for details).[36,37]

Arrhenius plots (Figure 5) constructed as the logarithm of the catalyst process rate [Ln(λ)] versus the reciprocal of the reaction temperature (K^{-1}) have contributed to better distinguish among the catalytic performance of ^{k}Ni/SiC catalysts operated under the two heating setups (Figure 3). Expectedly, when CO_2 methanation was carried out under the JH mode, the three catalysts behave similarly from a kinetic viewpoint, showing almost equal activation energy (curves' slope in Figure 5A and E_a values in Table 2) for processes operated under identical conditions. Moreover, calculated E_a values were in excellent agreement with the related literature data for the methanation process.[38−40] Reversely, IH showed important deviations in the curves' slope (Figure 5B), hence implying relevant alterations of the activation energy values associated to the process.

As Table 2 shows, the higher the catalyst metal loading, the lower is the activation energy (E_a) for the inductively heated methanation process and thus the higher is the ΔE_a(JH − IH) gap measured for the reaction operated under different heating configurations.

It is evident that differences in the activation energy values (ΔE_a) measured for the same process, operated with the same catalyst but under different heating schemes (JH vs IH), had to be ascribed to the existence of a temperature gap between the value measured (macroscopically) at the GF surface and those (real) of the RF-heated nano-objects (nickel active sites) at the SiC surface.

Several precedents from the literature have already demonstrated the existence of important temperature discrepancies (up to orders of magnitude)[17] between values reached at the surface of RF-heated nano-objects (metal NPs) and those measured macroscopically using a remote-sensing thermometer on the bulk materials.[18,41−43] The temperature measurement at the level of single-catalyst particles (especially for magnetically responsive elements) remains a challenging issue to be addressed, and it becomes even more tricky under operando conditions in severe experimental environments.[14,19−21] Anyhow, from the analysis of curves in Figure 4A−C, it can be inferred that the maximum difference on the x-axis (ΔT, °C) between two points at the same CO_2 conversion (X_{CO_2} on JH and IH curves) corresponds to the maximum ΔT value (ΔT_{max}) between the "macroscopic" temperature measured at the GF disks and that actually reached at the RF-excited nickel particles. Accordingly, 26 ± 3, 81 ± 4, and 95 ± 4 °C are the ΔT_{max} values between GF and Ni NPs in the RF-heated Ni/SiC catalysts containing 10, 15, and 20 wt % of metal NPs, respectively.

As expected, such a ΔT value varies as a function of the magnetic properties of Ni NPs, hence their mean particle size as well as the dependence of the nickel specific saturation magnetization (M_s) from the temperature (Section 3.4 for details).

On the Origin of ΔT Values in RF-Heated ^{k}Ni/SiC Catalysts Applied to the CO_2 Methanation Reaction. There are no doubts that the two heating configurations (JH and IH) hold distinct thermal and energetic features. Indeed, the RF heating of a GF-sandwiched catalyst always occurs in a "cold-wall reactor" modality,[20] hence avoiding any pre- and postheating of reagents and products, including that of the whole reactor volume and its peripheral walls. Such a configuration fosters (among the others) the reaction thermodynamics by favoring H_2O condensation just after the (hot) catalytic bed and reduces all thermal inertia phenomena typically encountered on furnace-based reactors while guarantying more sustainable and energy-saving catalytic schemes.[12]

Similar benefits linked to a more convenient heat management at the catalytic reactor have recently been commented by others for different gas-phase processes.[44,45]

It is clear that classical heat transfer by conduction/radiation (JH) applies to both heating configurations (JH and IH) proposed in this work. Under IH, the GF-sandwiched catalyst realizes a sort of micro-JH reactor. The thermal dissipation caused by the electromagnetically induced eddy currents flowing through the GF fibers can be considered as the main source of external heating (Figure 3B) for the catalyst active sites via classical conduction/radiation heat exchange. As an electrical semiconductor, SiC is not suitable to directly convert electromagnetic energy into heat at the catalytic bed; however, its thermal conductivity conveys the heat produced by the GF disks to the catalyst-active sites. Assuming the methanation exothermicity as independent from the nature of the adopted heating setup, under IH, the electrically conductive and magnetic nickel deposits (catalyst active phase) undergo

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ACS Sustainable Chem. Eng. XXXX, XXX, XXX−XXX

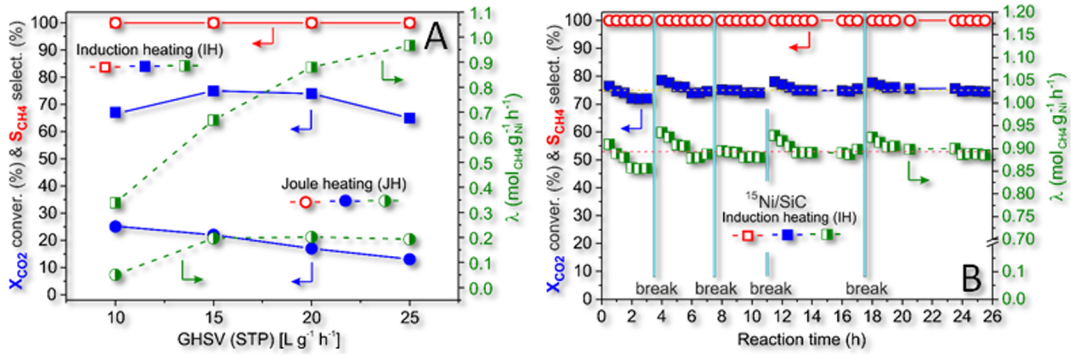

Figure 6. (A) X_{CO_2} and productivity rate (λ) dependence from the applied GHSV (L g^{-1} h^{-1}) for methanation processes operated on ^{15}Ni/SiC as a catalyst under the JH (round symbols) and IH (square symbols) mode. (B) Long-term methanation test at 20,000 mL g^{-1} h^{-1} as GHSV under the discontinuous mode using the inductively heated ^{15}Ni/SiC catalyst. Each break corresponds to the reactor switching-off overnight. Other common reactional conditions for A and B: $[CO_2]$ = 20 vol %; $[H_2]$ = 80 vol %; H_2-to-CO_2 ratio = 4; catalyst weight = 0.6 g; reaction temperature = 300 °C, atmospheric pressure.

dedicated heating paths.[46] In particular, eddy currents (or Foucault currents)[47,48] flowing through the larger metal aggregates and hysteresis loss[49,50] phenomena can induce local heating directly at the metallic phase. Hysteresis loss depends from the specific saturation magnetization (M_s) of the metal particles. It is a key property of ferromagnetic particles and varies as a function of the metal NP size and their ultimate temperature. Kuz'min demonstrated with a simple analytical representation the shape of the temperature dependence[51] for bulk Ni NPs. He properly described the finite-temperature properties of these ferromagnets in the −273.15 °C Curie temperature (T_c, °C; $^{Ni}T_c$ = 355 °C)[52] range, with the latter value corresponding to the temperature where M_s vanishes.[36] Duan and co-workers finally combined the morphological properties (TEM and XRD) of various grain-sized Ni NPs prepared by the autocatalytic reduction of a Ni^{II} salt with the M_s size dependence. Their study provided a useful model for the calculation of the experimental M_s value for similarly prepared Ni NP-based catalysts in the form of spontaneously surface-passivated (NiO-coated) systems like ours (see Section 3.1 for details). Based on their model (eq 4) and assuming a mean size of our Ni NPs of 13, 21, and 26 nm with an average thickness of the NiO thin layer for all catalysts of about 0.5 nm (see also Figure S4B), we calculated M_s values comprised between 47.5 and 52.4 emu/g (see Table 2), in excellent accordance with the Ni NP size/M_s dependence reported in the literature.

$$M_s^{exp} = \frac{\sigma_s^{bulk} \times \frac{4}{3}\pi r^3 \times \rho_{Ni}}{\frac{4}{3}\pi r^3 \times \rho_{Ni} + \frac{4}{3}\pi(R^3 - r^3)\rho_{NiO}} \quad (4)$$

where ρ_{Ni} = 8.8 g cm^{-3}, ρ_{NiO} = 6.827 g cm^{-3}, σ_s^{bulk} = 57.50 emu/g, R = mean radius of Ni NPs from XRD analysis, and r = (R − average thickness of a NiO thin layer).

The higher the M_s value, the higher is the hyperthermic efficiency or specific absorption rate of the nickel-based sample and thus the higher is its capacity to act as a heat susceptor[53] once immersed in an AC magnetic field.[54] The increasing values of ΔT_{max} measured on Ni/SiC samples with variable nickel-loading and nickel particle size (Figure 4A−C) are perfectly in line with these conclusions. Interestingly, JH and IH curves recorded in Figure 4A−C present similar converging trends in close correspondence to the $^{Ni}T_c$ value (355 °C). These trends led us to conclude that the extra heat (ΔT) generated under IH at the catalytic nickel sites was essentially due to hysteresis loss dissipation phenomena that were definitively suppressed when the metal sites became paramagnetic,[55,56] that is, above $^{Ni}T_c$. Accordingly, it can be concluded that eddy current contributions are almost negligible, whatever may be the nickel loading in the three catalysts in comparison. The moderate or null contribution from eddy currents was finally confirmed by the increasing X_{CO_2} conversion gap (or λ gap) measured with the two ^{k}Ni/SiC catalysts at higher metal loadings (k = 15 and 20 wt %) operated under JH and IH at temperatures >355 °C (above $^{Ni}T_c$). Under these conditions, the higher the catalyst particle size, the higher is the X_{CO_2} conversion gap between the two processes. Because eddy currents are directly proportional to the square of the NP radius, their contribution should follow an opposite trend to that recorded for catalysts ^{15}Ni/SiC and ^{20}Ni/SiC operated in CO_2 methanation at temperatures >$^{Ni}T_c$.

According to the observed trends of X_{CO_2} versus temperature recorded where the Ni NPs become paramagnetic (yellow sections of Figure 4A−C), it can be concluded that catalyst heating occurred through convection/conduction only. For the two RF-heated catalysts at higher Ni loading (^{15}Ni/SiC and ^{20}Ni/SiC), the reduced catalyst process rates for temperatures > $^{Ni}T_c$ are then ascribed to a less-effective JH transfer in the micro-JH reactor (GF-sandwiched catalyst) with respect to the classical external furnace. In contrast with the classical furnace, the formally cold walls of the micro-JH reactor facilitate a more rapid heat dissipation from the catalytic bed. Therefore, it can be inferred that this phenomenon in combination with the suppressed magnetic properties of Ni particles further contributed to the observed decrease in the catalysts' performance.

Effect of the Reactant Flow Rate (GHSV) on the Methanation Performance of a JH or IH ^{15}Ni/SiC Catalyst. The influence of the reactant space velocity (GHSV) was deliberately investigated on ^{15}Ni/SiC as one of the most representative samples from this catalyst series at a temperature of 300 °C where the ΔX_{CO_2} and $\Delta\lambda$ values measured under the two heating configurations (JH and IH) were the highest (Figure 4B and Table S1, entries 15−16). As Figure 6A shows, selectivity toward CH_4 laid constantly over 99% with no detectable traces of any other reaction byproduct, whatever may be the adopted heating configuration and the gas

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ACS Sustainable Chem. Eng. XXXX, XXX, XXX−XXX

flow applied to the reactor in the 10−25 L g^{-1} h^{-1} GHSV range.

As far as X_{CO_2} and λ values are concerned, the two heating configurations translated into radically different catalyst behaviors. Under the JH mode, X_{CO_2} decreased for increasing flow rates and catalyst productivity (λ) remained substantially unchanged throughout the last three reagent rates. When the process was operated under IH, an initial X_{CO_2} increase was observed and the catalyst productivity grew constantly (and appreciably) for increasing reactant flows. It should be stressed that $\Delta\lambda$ in ^{15}Ni/SiC operated under the two heating schemes (JH and IH) and at increasing reactant flow rates (from 10,000 to 25,000 as GHSV) increased over 190% (Table S1, entries 15−16 vs 21−22). There were few doubts that different values and trends in X_{CO_2} measured within the two heating configurations at increasing GHSVs reflected a radically different control of the temperature at the catalytic bed of the two reactors. All X_{CO_2} decreasing trends measured at increasing GHSVs can be claimed as the consequence of several factors such as: (i) an oversaturation of the metal active sites; (ii) a reduced contact time of reagents with the catalyst active phase; and (iii) a reduced catalyst temperature due to a more effective solid−gas heat exchange at increasing reactant flow rates. All these phenomena may contribute to reducing X_{CO_2} when GHSVs increase. However, i and ii items certainly do not justify the growing trend of X_{CO_2} measured under IH when the reaction was operated between 10,000 and 15,000 GHSVs. In contrast to classical JH reactors, temperature swings at the catalytic bed caused by growing flow rates (warming) and increased solid−gas heat exchanges (cooling) are rapidly controlled and compensated (with almost no thermal inertia) by a fast modulation of the current flowing through the inductor coils (remote-sensing thermometer connected to the inductor through a PID controller).

This excellent catalyst temperature control is also at the origin of a prolonged stability and durability of inductively heated catalysts on methanation run. Figure 6B refers to a long-term methanation test operated with the RF-heated ^{15}Ni/SiC catalyst at 300 °C with 20,000 mL g^{-1} h^{-1} as GHSV and in a discontinuous process (successive reactor shut-downs; breaks) as to add a further stress factor to the long catalytic trial (>25 h). As it can be seen, after an initial stabilization, the catalyst constantly laid on an average X_{CO_2} = 75 ± 2% with a quantitative methane selectivity and a productivity (λ) that closely approached 0.9 mol_{CH_4} g_{Ni}^{-1} h^{-1}.

The combination of the IH setup with the inherent thermal conductivity of SiC supports reduces all classical drawbacks associated to catalyst deactivation on run. TEM analysis of the catalytic material before and after the long-term run has demonstrated the superior stability of the catalytic system once operated under IH. Indeed, neither relevant changes in the NP size distribution (sintering) nor appreciable catalyst coking phenomena after long-term runs were revealed (Figures S5 and S6).

CONCLUSIONS

In summary, we compared ^{k}Ni/SiC composites at variable metal loading as catalysts for the Sabatier process under two different heating configurations (JH vs IH). The study has unambiguously demonstrated the superior performance, stability, and durability of catalysts operated under the less-conventional IH setup. The superior performance of RF-heated catalysts (already at relatively low temperatures) basically stems from a different heat management at the catalytic bed. The comparative analysis between the two heating schemes along with the study of process kinetics has offered a practical and simple tool to the estimation of the temperature gap between that measured directly at the main heat source and that (real) of the RF-heated nano-objects (metal NPs). If we assume any catalyst heating/cooling contributions (i.e., reaction exothermicity; solid−gas heat exchanges at varying GHSVs; and heat dissipation by the SiC support) as equal regardless of the nature of the heating configuration at work (IH and JH), such a temperature difference is unambiguously associated to the distinctive heat dissipation properties (eddy currents and hysteresis loss) of the electrically conductive and magnetic nickel particles immersed in the AC magnetic field.

Besides the evident benefits of the IH technology applied to the methanation process in terms of X_{CO_2} and process rates (λ) already under nominally low reaction temperatures, the virtual absence of thermal inertia phenomena and the subsequent fast modulation of the temperature directly at the catalytic bed hold unique advantages in terms of process safety (cold-reactor walls) and reduction of energy wastes (neither pre- and postcatalyst heating of reagents and products nor that of the whole reactor volume and its peripheral walls). Finally, the choice of silicon carbide as a support for the metal active phase has guaranteed a better temperature control at the catalytic bed. Indeed, SiC thermal conductivity allows the bidirectional heat transfer between the GF disks (susceptors under IH) and the Ni NPs, avoiding the formation of local hot spots that reduce process selectivity and the catalyst lifetime.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acssuschemeng.1c07217.

SEM, HRTEM, BET, and pore size distribution (BJH) of ^{k}Ni/SiC (k = 10, 15, and 20 wt %); XPS survey and Ni $2p_{3/2}$ of ^{15}Ni/SiC; and X_{CO_2} and catalyst specific rate (λ) for CO_2 methanation with ^{k}Ni/SiC (k = 10, 15, and 20 wt %) as catalyst(s) at variable reaction temperatures, operated under the JH or IH mode (PDF)

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Notes

The authors declare no competing financial interest.

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