CO_2 methanation with high-loading mesoporous Ni/SiO_2 catalysts: toward high specific activity and new mechanistic insights

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Abstract

In the power-to-gas scenario, surplus renewable electricity is stored in the form of methane, by reacting green hydrogen with waste CO_2 through the Sabatier reaction. Low-cost catalysts that feature a high activity at low temperature are needed. We disclose the sol-gel preparation of high-loading mesoporous Ni/SiO_2 catalysts. (HR)-TEM, XRD, N_2 physisorption, and H_2 chemisorption show that small Ni particles (<5 nm) are obtained, even at loading up to 38 wt%. The best catalyst reached a specific activity of 10.2 $\mu mol_{CH4}.g^{-1}.s^{-1}$ at 250 °C (TOF = 0.0155 s^{-1}; almost 3 times higher than a reference catalyst prepared by impregnation). Being based on inert silica, these catalysts are ideal model materials to elucidate the reaction mechanism on nickel. Combining CO_2-TPD, in-situ CO_2-DRIFTS, and TPSR with DFT calculations, we show that CO_2 methanation follows mostly the RWGS+CO-hydrogenation and the formate pathways, the former being dominant at low temperature.

Keywords

CO_2 methanation; Nickel nanoparticles, sol-gel; mesoporous catalyst; CO_2 hydrogenation mechanism

1. Introduction

Combustion of fossil fuels (coal, petroleum, and natural gas) is still the dominant way to meet the energy demands of the global society, but the related CO_2 emissions are causing serious environmental damage, linked to global warming and seawater acidification.[1, 2] Therefore, drastic efforts are being made to decrease emissions and mitigate atmospheric CO_2 concentration. A straightforward strategy to reduce anthropogenic CO_2 emission is carbon capture and storage (CCS) applied at point sources. However, an important limitation of this strategy is the energy penalty associated with the regeneration of the sorbents, for CO_2 purification, compression, transportation and storage.[3] Considering carbon dioxide as a carbon feedstock, CO_2 conversion and utilization (CCU) represents an attractive and promising strategy.[4] If (and only if!) fueled by "green H_2" (i.e. obtained by water electrolysis[5-7] or photocatalysis[8-10]), the hydrogenation of CO_2 to methane constitutes a potentially scalable method to store intermittent renewable energy into a product with a high energy density, which can be easily stored, transported and used in the existing industrial infrastructure.[11-13] This strategy could also represent an effective move to lessen our dependence on fossil-based methane and instead promote local energy independence.

CO_2 methanation (also called the Sabatier reaction) is an exothermic reaction, favored thermodynamically at low temperature ($CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O$; ΔH = -165 kJ/mol) but limited kinetically because of the high stability of CO_2 that has to undergo a 8-electron reduction.[14] While various transition metals (Ru, Rh, Pd, etc.[15-22]) in their supported and highly dispersed form are active in CO_2 methanation, Ni remains the most effective choice, owing to the fact that Ni is both highly selective toward methane and relatively inexpensive. However, in order to achieve high CO_2 conversion, Ni-based catalysts need to be employed at relatively high temperatures (300-500 °C), which results in large energy input, high operational costs for large-scale production, and negative impact on catalyst stability.

Ni can be finely dispersed in the form of nanoparticles on various oxide supports (SiO_2, Al_2O_3, TiO_2, CeO_2, ZrO_2) to form active methanation catalysts.[23-26] Different

strategies have been implemented to improve the activity at low temperature, such as doping with a second metal[25, 27, 28], tuning the metal-support interaction[26], controlling the metal nanoparticles size and shape[29-31], etc. Those methods mainly focus on improving the intrinsic activity of the catalyst, by tuning the properties of the active sites (e.g., improve the reducibility of NiO, enhance CO_2 activation). Apart from this, increasing the *amount* of active sites is also a direct and effective way to boost the specific activity of a catalyst. Using a support with high specific area, such as molecular sieves, mesoporous oxides, MOFs, etc. can help obtaining catalysts with small nickel particles (high dispersion).[32-34] However, the optimal Ni loading generally does not exceed 20%, as the aggregation of nickel nanoparticles is observed with the further addition of Ni.[32, 35, 36]

Sol-gel methods are primed to prepare composites with tailored textural and chemical properties, and has been widely used in catalyst preparation.[37] For example, Lin et al. prepared a Ni-based catalyst (7.9 wt.%) supported on a mesoporous Al_2O_3-ZrO_2 support synthesized by a single-step epoxide-driven sol-gel method, which presented a high catalytic activity (19 μmol g^{-1} s^{-1} at 300 °C) and CH_4 selectivity (99.3 %) with excellent stability.[35] Ye et al. reported on a nanostructured Ni/CeO_2 catalyst (16.75 wt.%) prepared by a facile sol-gel method, the activity of which (21.1 μmol g^{-1} s^{-1}, 300 °C) was up to 48 times higher than the benchmark Ni/CeO_2 catalysts prepared by state-of-the-art impregnation method.[24] But the optimal Ni loading of those catalysts is still limited to relatively low values (10-20 wt.%). Recently, Yang et al. reported a sol-gel strategy using ethylene glycol, zinc nitrate, and tetraethyl orthosilicate as precursors to prepare ZnO/SiO_2, in which the loading of well-dispersed ZnO nanograins reached up to 57%.[38]

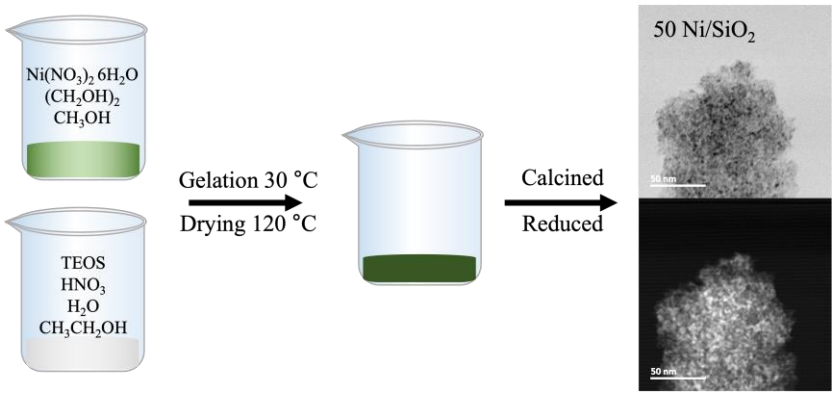
This report prompted us to explore the sol-gel preparation of high-loading and high dispersion Ni/SiO_2 catalysts, reasoning that high loading Ni with small particle and high dispersion can provide more active site for CO_2 methanation. With these new catalysts in hands, and using a combination of experimental and computational data, we also address a long-standing debate on the reaction mechanism. In fact, many experimental and theoretical studies have been conducted to elucidate the possible

pathways leading to methane (i.e. the "formate route" and the "CO route"[31, 39]) but such discussions are usually focused on doped active phases and/or on the role of metal-support interactions in creating oxygen vacancies. Here, with small Ni nanoparticles embedded in an inert and stable silica matrix, we can decipher the mechanism as it is occurring on Ni. Our data allowed establishing that formate, carbonyl, and C species from the adsorption and activation of CO_2 participate in the catalysis in three pathways, among which the RWGS+CO hydrogenation pathway has the rate determine step with the lowest energy barrier and is dominated at low reaction temperature.

2. Experimental section

2.1. Catalyst preparation. A series of mesoporous Ni/SiO_2 catalysts with different Ni loading were synthesized by a sol-gel method (Scheme 1). Typically, 0.6 mL anhydrous ethanol (EtOH), 0.8 mL distilled H_2O, and 1.9 mL HNO_3 (4M) were added to 5.6 mL tetraethyl orthosilicate (TEOS) and stirred for 1 h to obtain a clear SiO_2 sol. The required amount of nickel nitrate hexahydrate was dissolved in ethylene glycol (EG) and methanol (V_{EG}:$V_{methanol}$ = 3:2) was added to obtain a 2 M nickel nitrate solution. The solution was then added to the SiO_2 sol and stirred for another 1 h. The obtained slurry was aged at 30 °C for 12 h and dried at 120 °C for another 12 h to form a gel. The dried gel was calcined in air at 300 °C (1 °C/min) for 2 h, and then at 500 °C (1 °C/min) for an additional 2 h. The calcined sample are denoted as "n NiO/SiO_2", where n represents the theoretical amount of NiO in wt%. The calcined catalyst was reduced in situ in the reactor (see below) under a H_2/He flow, and the corresponding samples were denoted "n Ni/SiO_2". To examine the role of EG, Ni/SiO_2-ME was also prepared in the same way using only methanol as solvent, respectively.

As a benchmark, we prepared 50 Ni/SiO_2-IM by an impregnation method. 5.84 g $Ni(NO_3)_2 \cdot 6H_2O$ was added to 20 mL distilled water, and then the solution was mixed with 1.5 g SiO_2 (purchased from Sigma-Aldrich, CAS number: 112926-00-8, pore volume: 1.15 cm^3/g, 1.5 Å), followed by vigorously stirring at 80 °C until water was completely evaporated. The obtained solid was dried at 120 °C for 12 h and calcined in the same way as the Ni/SiO_2 sol-gel catalysts series.



Scheme 1. Description of the preparation of Ni/SiO_2 catalysts by the ethylene glycol-assisted sol-gel method. On the right: Bright Field (BF) STEM and High Angle Annular Dark Field (HAADF) STEM micrographs showing an amorphous disordered silica matrix in which Ni nanoparticles are embedded.

2.2. Characterization. The N_2 adsorption-desorption analysis was carried out by a Tristar 3000 (Micromeritics, USA) instrument. The sample was degassed at 250 °C for 3 h to remove physical absorbed water and impurities on the surface before the measurement. The total pore volume (V_p) was calculated from the amount of nitrogen absorbed at a P/P_0 of 0.98 and the pore size distribution of each catalyst was drawn from the desorption branch with the Barrett-Joyner-Halenda (BJH) method.

Transmission electron microscopy (TEM) measurements were operated on JEOL2100F microscope working at 200kV with a Cs corrector and equipped with a CCD camera and BF Gatan and HAADF Jeol detectors. The samples were prepared by ultrasonic dispersion of the powders in water and a droplet of the dispersion was then placed onto a carbon-coated copper grid. The software of Nano Measurer 1.2 was used to calculate particle sizes.

Elemental analysis of as-prepared catalysts was carried out by an inductively coupled plasma atomic emission spectroscopy (ICP-AES).

H_2 chemisorption at 30 °C was used to measure the Ni dispersion using ASAP 2010C apparatus from Micrometrics. Catalyst weight ca. 200 mg was loaded into a Pyrex tube, and subsequently degassed in He for 30 min. After evacuation, the sample was reduced in pure H_2 at 500 °C for 2 h (same as in situ reduction for methanation, see Section 2.3) followed by purging with He for 1 h and adsorption of H_2. Two isotherms were measured in the range of 0.13-60 kPa. The first isotherm accounts for reversible

physisorption and irreversible chemisorption. The sample was evacuated at 30 °C to desorb reversibly adsorbed H_2. The second isotherm was then measured which accounts only for the reversibly adsorbed H_2. The subtraction of the linear part of the two isotherms gave the total amount of irreversibly chemisorbed H_2. The amount of surface Ni atoms was calculated from the amount of chemisorbed H_2 assuming that the chemisorption stoichiometry is H:Ni = 1.

X-ray diffraction (XRD) analyses was performed with a Bruker AXS-D8 Advance (Germany) diffractometer using Cu Kα (γ = 1.78 Å) radiation at 35 kV and 40 mA.

X-ray photoelectron spectroscopy (XPS) experiments were carried out using an SSX 100/206 spectrometer (Surface Science Instruments, USA) with Al Kα radiation operated at 10 kV and 20 mA. The binding energy scale was calibrated on the Si 2p peak, fixed at 103.5 eV.[40]

H_2-temperature programmed reduction (H_2-TPR), CO_2 temperature-programmed desorption (CO_2-TPD) and CO_2 temperature-programmed surface reaction (CO_2-TPSR) measurements were performed on a Hiden Autochem II 2920 instrument with an on-line QIC20 mass spectrometer (MS). For the H_2-TPR, the samples (50 mg) were pretreated with high purity Ar at 350 °C and a flow rate of 30 mL/min for 0.5 h to remove water and other contaminants. When the samples were cooled down to room temperature, 5% H_2/Ar was introduced into the system at a flow rate of 30 mL/min. The MS signal and sample temperature were recorded while the temperature was increased to 900 °C at a heating rate of 10 °C/min. For the CO_2-TPD, 50 mg sample was reduced in-situ at 500 °C for 2 h in 5% H_2/Ar. After reduction, the gas was changed to Ar for 1 h to remove the adsorbed H_2. Then the sample was cooled down to 50 °C, and 15% CO_2/Ar was admitted for 1 h. The system was then purged by an Ar flow for 1 h at 50 °C. Finally, the catalyst was heated up to 900 °C at a rate of 10 °C/min in a flow of Ar. The process of CO_2-TPSR was similar with CO_2-TPD, except that the last stage was done with a mixture of 5% H_2/Ar. Besides, in some cases, the purge process after CO_2 adsorption was operated at other temperature. The signal of CO_2 and CH_4 was examined by MS with the m/z of 44 and 16.

In-situ CO_2 desorption diffuse reflectance infrared Fourier transform spectroscopy (DRIFTS) was collected using a Nicolet 6700 spectrometer. The catalyst was mixed with KBr (1:5 mass ratio) and 0.03 g of this mix was loaded into the chamber and in-situ reduced at 500 °C for 1 h again in flowing H_2 and He. Then, the gas was changed to He to flush the sample for 30 min at 500 °C to remove residual H_2. Afterwards, the temperature was decreased to a certain temperature (450, 170, 120 or 30 °C, chosen according to the results of CO_2-TPD) and the background was recorded. Subsequently, CO_2 was flowed onto the sample for 1 h and then the gas was changed to He. Finally, the chamber was set to the desired temperature (30, 120, 170 or 450 °C) and the spectrum was recorded when reaching a steady state.

2.3. CO_2 methanation. The catalytic performance of the catalysts was measured in a continuous flow gas-phase microreactor, at atmospheric pressure. In a typical run, 50 mg of catalyst was placed in the reactor (i.d. 6 mm). Before reaction, the catalyst was reduced in situ at 500 °C for 2 h in a 50% H_2/50% He flow (40 mL/min) and then cooled down to 200 °C. Afterwards, a mixture of 10% CO_2 and 40% H_2 balanced with He was introduced to the reactor. The total gas flow rate was 20 mL/min. The catalytic tests were carried out in step mode in the 200 °C to 400 °C range. Each temperature was maintained for 88 min, allowing for 4 GC analyses. The gas exiting the reactor was analyzed on a gas chromatograph (Varian CP3800), equipped with Hayesep Q, Molsieve 5A, and CP-Sil-5CB columns. The separated gases were analyzed with a flame ionization detector (CH_4) and a thermal conductivity detector (CO and CO_2). All transfer lines were maintained at 125 °C to avoid water condensation. Conversion (X_{CO2}) and selectivity (S_{CH4}) were calculated according to the following equations:

$$X_{CO2} = \frac{F_{CO_2,in} - F_{CO_2,out}}{F_{CO_2,in}}$$

$$S_{CH4} = \frac{F_{CH_4,out}}{F_{CO_2,in} - F_{CO_2,out}}$$

where F is the molar flow rate. The turnover frequency (TOF) was calculated by the following equation:

$$\mathrm{TOF}\ (s^{-1}) = \frac{\frac{X_{CO_2}}{V_m} \times F_{CO2,in}}{\text{mole of surface Ni atoms}}$$

We verified experimentally there is no heat and mass transfer limitations in the tested conditions by varying the amount of catalyst and flow and changing the size of the catalyst pellets (see supplementary information, Fig. S1). To build the Arrhenius plots in the 210-290 °C temperature range, a high GHSV (336000 mL g^{-1} h^{-1}) was applied, maintaining the CO_2 conversion is below 15%.

2.4. Computational methods. All calculations were carried out by using the Dmol^3 program in Materials Studio[41, 42]. Density functional theory calculations within the generalized gradient approximation (GGA) and the Perdew−Burke−Ernzerhof (PBE) functional[43, 44] were carried out to study the mechanism of CO_2 methanation on Ni(1 1 1), which is considered as the most active and stable surface of Ni-based catalysts for CO_2 methanation[31, 45]. Double numerical plus polarization (DNP) basis sets were used[46], and all calculations were spin-unrestricted to account for the magnetic properties of Ni. A Fermi smearing of 0.05 Hartree was utilized. The vacuum between the slabs was set to span a range of 12 Å to ensure no significant interaction between the slabs. A 3 × 3 slab (five layer, see Fig. S2) was chosen to represent the Ni(1 1 1) surface for CO_2 methanation. The bottom three layers of the nickel slab were fixed, whereas all other atoms were allowed to relax. The convergence criteria for structure optimization and energy calculation were set to 1.0×10^{-6} eV/atom for SCF, 1.0×10^{-5} eV/atom for energy, 0.03 eV/Å for maximum force, and 1.0×10^{-3} Å for maximum displacement. Transition state (TS) search was performed at the same theoretical level with complete linear synchronous transit/quadratic synchronous transit (LST/QST) method.[47]

3. Results and discussion

3.1. Structural and morphological characterization. Textural properties of the NiO/SiO_2 with different Ni loading were examined by nitrogen adsorption-desorption analyses. Isotherms are presented in Fig. 1 and the detailed physicochemical characteristics of NiO/SiO_2 are shown in Table 1. The specific surface area of the

catalysts with 30 and 40 wt.% of nominal NiO loading is as high as ~520 $m^2.g^{-1}$. The specific surface area tends to decrease with the further increase of Ni loading, but at 60 wt.% nominal NiO loading, it still reaches as high as 345 $m^2.g^{-1}$. All samples exhibit type IV adsorption isotherms with an H1-type hysteresis loop (Fig. 1a), indicating the presence of mesopores.[48] With increasing Ni content, the total pore volume (V_p) and the average pore diameter increases firstly and then decreases for the 60 NiO/SiO_2, and 50 NiO/SiO_2 is the most porous. Furthermore, the micropore volume (V_{Mi}) decreases when the Ni loading increases, while the mesopore volume (V_{Me}) shows a similar trend as total pore volume. The impregnated catalyst (50 NiO/SiO_2-IM) has a smaller specific surface area, as compared to the corresponding catalyst made by sol-gel and larger pores.

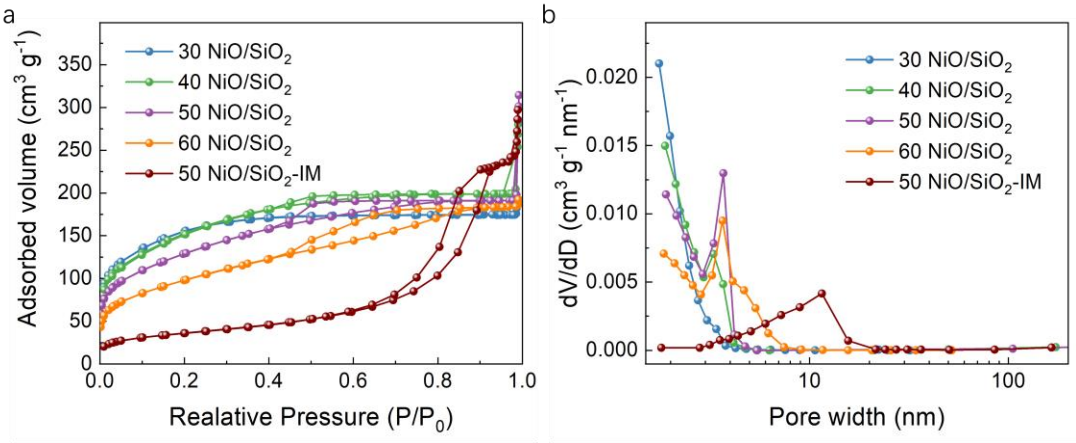


Fig. 1. (a) N_2 adsorption-desorption isotherms and (b) BJH pore size distributions of NiO/SiO_2 catalys

Table 1. Physicochemical characteristics of the NiO/SiO_2 and Ni/SiO_2 and their CO_2 methanation TOF values.

Sample	S_{BET} (m^2/g)	V_p (cm^3/g)	V_{Micro} (cm^3/g)	V_{Meso} (cm^3/g)	D_p (nm)	Ni content[a] reduced (%)	Ni dispersion[b] reduced (%)	Ni particle size[c] reduced (nm)	TOF (s^{-1}, 250 °C)
SiO_2	648	0.43	0.32	0.11	2.3	-	-	-	-
30 NiO/SiO_2	520	0.28	0.25	0.03	2.1	23	13.8	2.3	0.0128
40 NiO/SiO_2	527	0.43	0.21	0.19	3.2	31	12.9	2.8	0.0141
50 NiO/SiO_2	455	0.49	0.15	0.3	4.2	38	11	4.6	0.0155
60 NiO/SiO_2	345	0.3	0.08	0.18	3.4	45	10.1	7.1	0.0136
50 NiO/SiO_2-IM	126	0.46	-	0.46	14.2	38	6.1	41.0	0.0056

[a] Determined by ICP-AES measurement.

[b] Determined by H_2 chemisorption.

[c] Obtained from Scherrer equation.

The morphology and nanostructures of calcined and reduced catalysts are displayed in Fig. 2 and Fig. S3. TEM shows that nickel in 50 NiO/SiO_2 is uniformly distributed in the form of small nanoparticles, while large aggregates of nickel are observed in the impregnated samples (50 NiO/SiO_2-IM). Upon reduction, 50 Ni/SiO_2 maintains a uniform distribution of nanoparticles with an average size of 3.7 nm (Fig. 2c and 2d). The lattice spacing of 0.201 nm matches with that of (111) lattice planes of Ni (Fig. 2f). In contrast, Ni particles in 50 Ni/SiO_2-IM appear strongly agglomerated (Fig. 2h and 2i) and the Ni particle size reaches as high as 46 nm in size. Consistently, the dispersion – measured by H_2 chemisorption – was much higher for 50 Ni/SiO_2 (11%) than for 50 Ni/SiO_2-IM (6.1%). Similar to 50 NiO/SiO_2, small and uniformly distributed NiO and Ni particles are observed in 30 Ni/SiO_2 and 40 Ni/SiO_2 (Fig. S3a-S3d). However, aggregation is observed for the 60 NiO/SiO_2 and 60 Ni/SiO_2 (Fig. S3e and S3f). In the Ni/SiO_2 series, Ni dispersion linearly decreases with increasing Ni loading. It reaches 13.8%, 12.9% and 10.1% respectively for 30, 40 and 60 Ni/SiO_2 (Table 1).

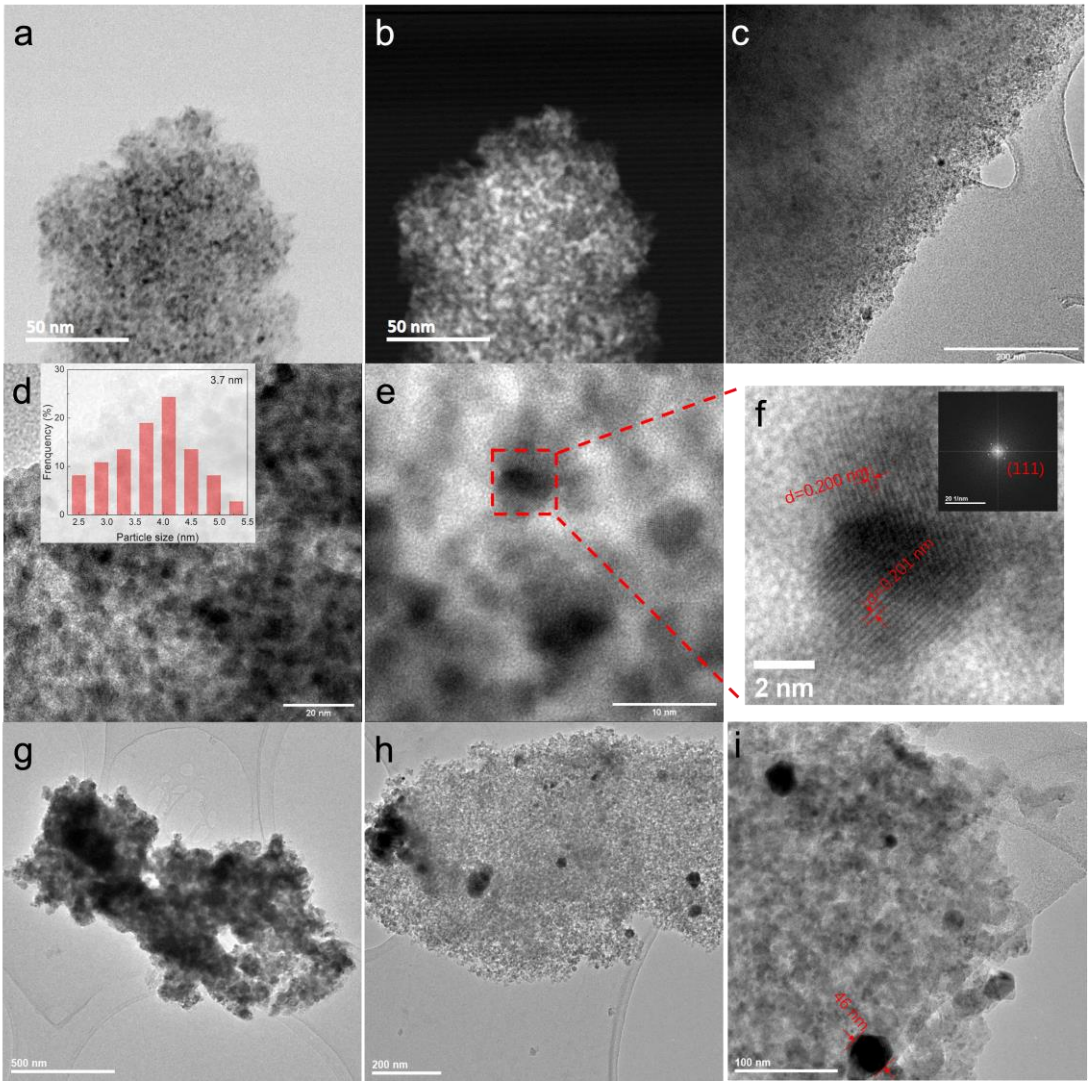


Fig. 2. (a) BF-STEM image and (b) HAADF-STEM image of the 50 NiO/SiO_2, (c, d) TEM images and (e, f) HR-TEM images, of the 50 Ni/SiO_2 catalyst (inset of (d) is the Ni particles size distribution; inset of (f) being its FFT pattern); (g) TEM image of the

50 NiO/SiO_2-IM, (h, i) TEM images of the 50 Ni/SiO_2-IM.

3.2. Characterization of the Ni phase. The XRD patterns of the calcined samples (Fig. 3a) show the diffraction peaks corresponding to the crystal structure of NiO (PDF 65-2901). These characteristic reflection peaks are located at 2θ around 37.3°, 43.3°, 62.9°, 75.2°, and 78.7°, attributed due to the diffractions from the (1 1 1), (2 0 0), (2 2 0), (3 1 1), and (2 2 2) planes of NiO, respectively. The XRD patterns of reduced catalysts (Fig. 3b) show metallic Ni reflections (PDF 04-0850) at 2θ = 44.5° (1 1 1), 51.8° (2 0 0), and 76.3° (2 2 0). Furthermore, small peaks at 2θ ≈ 30° and 65° attributed to NiO could also be observed, which can be attributed to the reoxidation of the reduced catalyst upon handling. Indeed, an in-situ XRD for the 50 Ni/SiO_2 catalyst (Fig, S4) confirmed that NiO species was fully reduced to Ni metallic after treated in H_2 for 2 h at 500 °C. The intensity of NiO diffraction peaks increases with the NiO content in calcined NiO/SiO_2 catalysts, and a similar trend is shown for the metallic Ni in the reduced Ni/SiO_2 catalysts, indicating that higher Ni loading resulted in the formation of larger crystallites, as presented in Table 1. The crystallite size of 50 Ni/SiO_2 estimated by the Scherrer formula is around 4.6 nm, which is consistent with the TEM results. The NiO/SiO_2-IM shows sharper and more intense NiO peaks and the Ni/SiO_2-IM has stronger Ni peaks, which suggests the metal crystallites size is much bigger prepared by IM as compared to sol-gel method and is also consistent with TEM observations. In this case, the crystallite size is estimated at 41 nm.

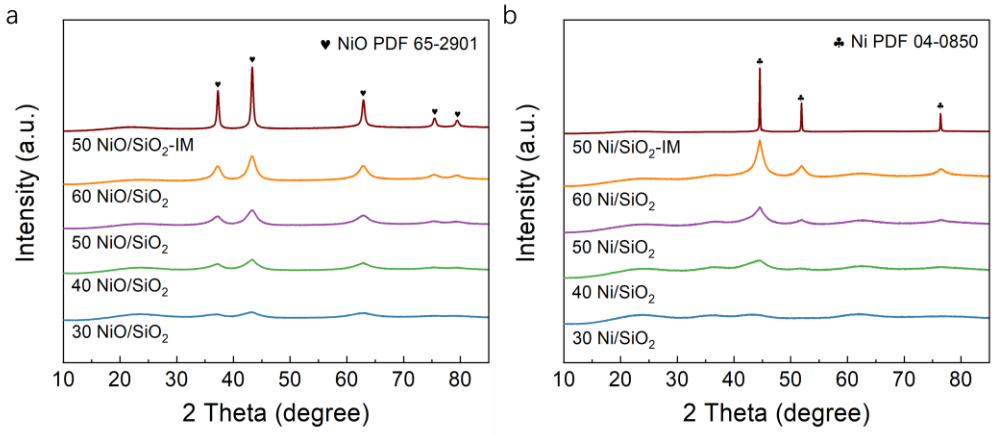


Fig. 3. The XRD patterns of (a) calcined and (b) reduced catalysts.

From the above, it appears that the ethylene glycol-assisted sol-gel route employed here allowed preparing high-loading Ni-SiO_2 catalysts with a high dispersion of small Ni nanoparticles. To highlight the beneficial effect of ethylene glycol, we also prepared 50 Ni/SiO_2-Me by sol-gel method with only methanol (no EG) being added during the synthesis of nickel nitrite solution. The Ni particle size of 50 Ni/SiO_2-Me (XRD pattern shown in Fig. S5a) calculated from Scherrer equation is ca. 16.3 nm, which is much bigger than that of 50 Ni/SiO_2 (4.6 nm). According to the literature, EG inhibits the agglomeration of metal species, as the metal nitrate reacts with EG through a redox reaction during the gel process to form stable carboxylate complexes.[38] The latter has a high decomposition temperature, so the sintering of the metal oxide is effectively inhibited. Furthermore, the textural properties are strongly affected by the presence/absence of EG (N_2 physisorption isotherms for 50 Ni/SiO_2-Me are presented in Fig. S5b). Specific surface area and pore volume of 50 Ni/SiO_2-Me only reach 378 m^2/g and 0.16 cm^3/g (to be compared with 455 m^2/g and 0.49 cm^3/g for 50 Ni/SiO_2), indicating that EG plays a significant role as a texturing agent.

XPS was also carried out to determine the surface composition and chemical state of the catalysts. The high resolution Ni $2p_{3/2}$ spectra of calcined catalysts (Fig. 4a and Fig. S6) exhibit a peak at 855.3 eV corresponding to Ni^{2+} and a shake-up satellite peak at 861.3 eV[49]. The XPS of the reduced sample (Fig. 4a) clearly show the co-existence of Ni^{2+} and metallic Ni^0 (peak at BE ≈ 852.4 eV). This appears inconsistent with the XRD results (showing only the metallic Ni phase in the reduced catalysts) but can be explained by surface passivation.[50] Two types of oxygen species can be detected by deconvoluting the O 1s peak (Fig. 4b and Fig. S6). The peak with BE at around 529.9 eV was ascribed to the surface lattice oxygen of NiO, whereas the second peak at 532.8 eV was attributed to Si-O-Si and surface adsorbed oxygen.[24, 51] Expectedly, for the calcined catalysts, Ni/O_{Ni} is approximately equal to 1. For the reduced catalysts, Ni/O_{Ni} increases markedly, consistent with the reduction of the NiO particles. This increase is more marked for higher Ni loading (Table S1), which indicates a more complete reduction (lower tendency to undergo surface passivation) of the larger NiO particle size.

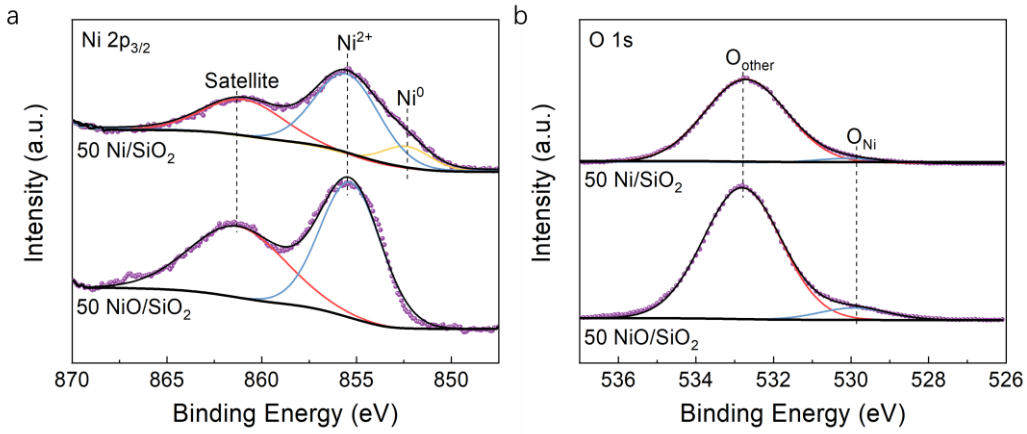


Fig. 4. XPS spectra of Ni $2p_{3/2}$ (a) and O 1s (b) for the 50 NiO/SiO_2 (calcined) and the 50 Ni/SiO_2 (reduced).

The reduction behavior of catalysts was investigated using H_2-TPR measurements, as shown in Fig. 5. Two reduction peaks are observed at about 370 °C and 530 °C, which can be ascribed to the reduction of highly dispersed NiO species moderately and strongly interacting with the support.[26] Here, the percentage of NiO reduced at lower temperature increases with the Ni loading (39, 48, 59, 64 % respectively for 30, 40, 50, and 60 Ni/SiO_2), which indicates that the proportion of strongly interacting NiO species decreases when the Ni loading increases.

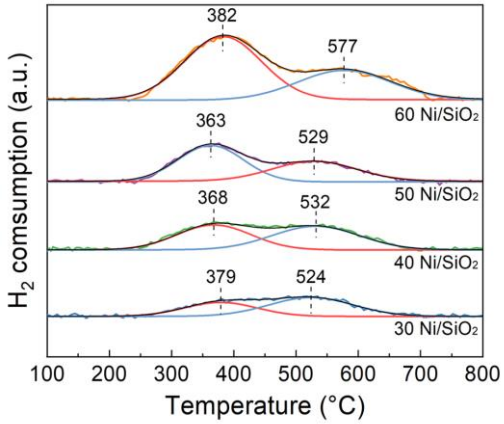


Fig. 5. H_2-TPR profiles of the NiO/SiO_2 catalysts.

3.3. CO_2 methanation. The catalytic performance of the materials was tested in the 200-400 °C range under 1.0 bar at a GHSV of 24,000 $mL \cdot g^{-1} \cdot h^{-1}$ (based on the total flow). Fig. 6a shows that all samples exhibit already some methanation activity at 200 °C. Then activity increases when reaction temperature increases and tends to level

off close to the theoretical equilibrium at 350 °C and 400 °C. At each reaction temperature, activity increases when the Ni loading increases from 23 to 38 wt.%. At 45 wt.%, activity appears to drop, consistent with the poorer Ni dispersion discussed above. A maximal CO_2 conversion of 84% with 96.5% CH_4 selectivity is obtained at 350 °C for the 50 Ni/SiO_2. 50 Ni/SiO_2 catalyst was also tested with the GHSV of 24,000 $mL \cdot g^{-1} \cdot h^{-1}$ at 300 °C for 50 h (Fig. S7) and showed excellent stability, maintaining CO_2 conversion and CH_4 selectivity above 76 % and 98 %, respectively. 50 Ni/SiO_2 catalyst is much more active than the 50 Ni/SiO_2-IM prepared by the more classical impregnation technique. For example, at 250 °C (where conversion is still far from the thermodynamic equilibrium), the catalyst prepared by sol-gel is about 4 times more active than the impregnated one. TOF values (considering the conversion, Ni loading and Ni dispersion) are also calculated and presented in Table 1. At 250 °C, 50 Ni/SiO_2 (0.0155 s^{-1}) is 2.8 times more active than 50 Ni/SiO_2-IM (0.0056 s^{-1}).

Also, we have collected published data corresponding to Ni and SiO_2-based catalysts tested in similar conditions (space velocity, pressure, temperature, gas composition) and translated them into specific activity ($\mu mol_{CH4}\ g_{cat}^{-1}\ s^{-1}$) considering only experimental data points that have been obtained far enough from the thermodynamic equilibrium, i.e. < 40% conversion. Fig. 6b shows that our sol-gel based catalyst outcompetes all other reported catalysts. This high specific activity is obviously to be related to the high Ni loading in our samples. If we normalize the performance by the Ni loading, our catalysts are lower than some of the others, showing that a better use of Ni is possible (see also the comparison of TOF values in Table S2). However, high specific activity is important from an engineering point of view, as it governs capital and operational expenditures for the methanation plant. It should be reminded that such high loadings were not accessible with previously reported preparation methods, as the performance dropped dramatically when pushing the loading above 10 or 15 wt.%, as a result of Ni aggregation and sintering (very poor dispersion). With the sol-gel method presented here, the loading can be increased above 20 wt.% and as high as 38 wt.% while maintaining high Ni dispersion and increasing the catalytic activity. It is only when

reaching 45 wt.% loading that the dispersion decreases markedly and that the specific activity starts to drop.

To have a better understanding of the catalytic behavior of these materials, we built the Arrhenius plot by carrying out the reaction with 50 Ni/SiO_2 between 210 and 290 °C (Fig. 6c). The CO_2 conversion is maintained below 15% (kinetic regime, far from thermodynamic equilibrium) at a high GHSV of 336000 ml g^{-1} h^{-1} to measure the intrinsic activity. Surprisingly, instead of one straight line, we observed a break in the Arrhenius plot, indicating that the apparent activation energy was markedly different below and above ~250 °C (82 kJ mol^{-1} and 99 kJ mol^{-1} respectively). This feature is usually attributed to competing reactions or reaction mechanisms.[52] In the next section, we discuss the possible implications of such findings by inspecting the mechanism from an experimental and computational perspective.

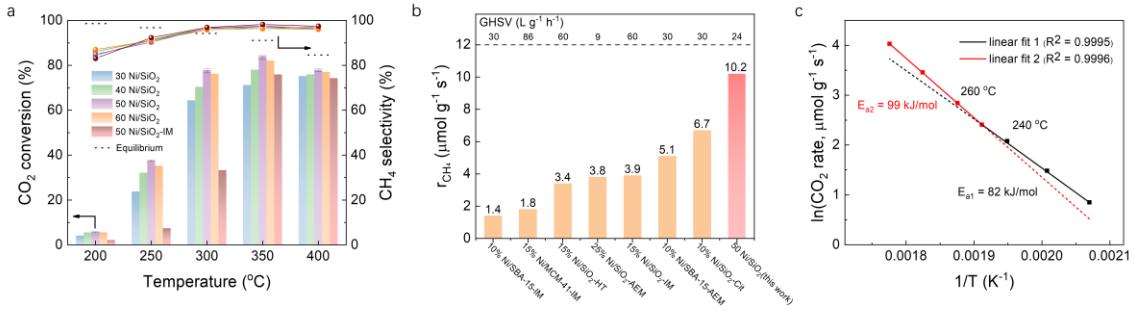
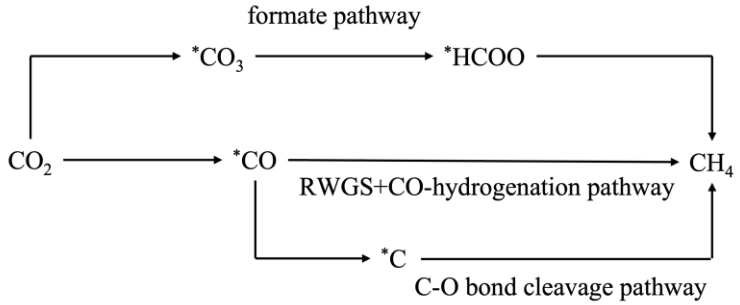


Fig. 6. (a) CO_2 conversion and CH_4 selectivity over the Ni/SiO_2, (b) The specific activity of 50 Ni/SiO_2 at 250 °C compared to other reported Ni/SiO_2 catalysts (10% Ni/SBA-15-IM prepared by impregnation method[53], 15% Ni/MCM-41-IM prepared by impregnation method[54], 15% Ni/SiO_2-HT prepared by hydrothermal method[55], 25% Ni/SiO_2-AEM prepared by ammonia evaporation method[56], 15% Ni/SiO_2-IM prepared by impregnation method[57], 10% Ni/SBA-15-IM prepared by ammonia evaporation method[53], 10% Ni/SiO_2-Cit prepared by combustion-impregnation method[58] and (c) Arrhenius plot of the 50 Ni/SiO_2.

3.4. Mechanism study.

Three reaction mechanisms have been proposed to describe the catalytic hydrogenation of CO_2: (i) the formate pathway, (ii) the reverse water gas shift (RWGS)+CO-hydrogenation pathway, and (iii) the C-O bond cleavage pathway (scheme 2).[31, 39, 59, 60] In the formate route, CO_2 is molecularly chemisorbed to form carbonate intermediates, which decompose to formate species and react with H_2

to produce methane. In the CO route, the CO_2 molecules undergoes a dissociative chemisorption, yielding a surface carbonyl and an oxygen atom that both react with H_2 afterwards. In the C-O bond cleavage pathway, the yielded carbonyl from the CO_2 dissociation can further dissociate to form carbon which then reacts with H_2.



Scheme 2. Possible reaction pathways of CO_2 hydrogenation to CH_4.

Many theoretical and experimental studies have been conducted to study the mechanism of CO_2 methanation on Ni-based catalysts.[61-64] However, there is no unified view on the path that governs catalytic activity. For Ni/CeO_2 catalysts, for example, the formate pathway and the RWGS-CO hydrogenation pathway were shown to occur in parallel, the latter mechanism being dominant, especially at low temperature.[50] On the contrary, on Ni/ZrO_2 and $Ni/(Mg,Al)O_x$ catalysts, the formate pathway was identified as the most plausible.[62, 63] Obviously, the support can have a great influence on the CO_2 methanation mechanism. Furthermore, using DFT simulation, Ren et al. claimed that the C-O bond cleavage pathway should prevail on Ni catalysts.[61] Clearly, there is a need to further inspect conflicting experimental observations and theoretical calculations. Here, we use a combination of temperature programmed surface reaction (TPSR) experiments and density functional theory (DFT) simulation in an attempt to decipher the different possible mechanisms at play in the relevant reaction temperature ranges.

CO_2-TPD tests were firstly performed to assess the CO_2 adsorption ability of the catalysts. As shown in Fig. 7a, the total CO_2 adsorption amount increases with the Ni loading. Furthermore, there is almost no CO_2 detected for the pure SiO_2 in the CO_2-TPD process (Fig. S9), confirming that CO_2 adsorption occurs on the surface of Ni. Three distinct desorption events can be observed, corresponding to three kinds of

adsorbed CO_2 species. DRIFTS coupled with CO_2 adsorption and desorption sheds light on the nature of these species (Fig. 7b). 50 Ni/SiO_2 was saturated by CO_2 and then flushed under He atmosphere at 30 °C before recording IR spectra. The spectrum features the clear signatures of bidentate carbonate (1665, 1484 cm^{-1}), bicarbonate (1622 cm^{-1}), monodentate carbonate (1521 cm^{-1}), and polydentate carbonate (1402 cm^{-1}).[31, 62] As the temperature is increased to 120 °C, the band for bicarbonate disappears, and a new band for multi-bonded carbonyl (1693 cm^{-1})[65-67] appears but is removed at 450 °C. Meanwhile, the band for monodentate carbonate decreases at 120 °C and disappears at 170 °C. To sum up, bicarbonate and monodentate carbonate species were desorbed at 120 and 170 °C, and the CO from the dissociation of CO_2 was desorbed at 450 °C.

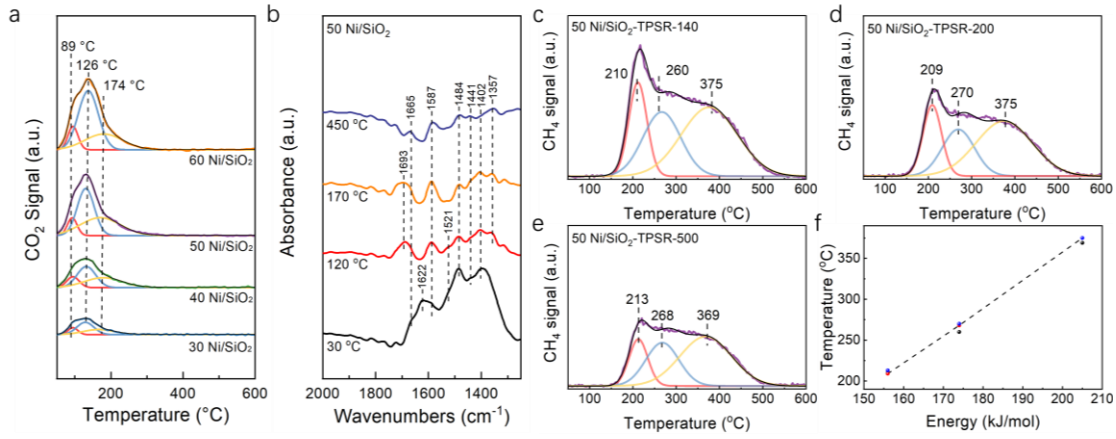


Fig. 7. (a) CO_2-TPD of profiles of the NiO/SiO_2 catalysts, (b) in-situ CO_2 desorption DRIFTS of the 50 Ni/SiO_2, (c-e) TPSR of 50 Ni/SiO_2 with different purge temperature, (f) relationship between the energy barrier of RDS for each pathway obtained from DFT and the temperature of CH_4 formation peak.

After having identified the nature of the adsorbed species and their stability over the catalysts, a set of CO_2-TPSR tests was designed to elucidate how these species dynamically interacts with the Ni/SiO_2 catalyst in the presence of H_2. Specifically, CO_2-TPSR experiment was performed by adsorbing CO_2 at 30 °C followed with the purge process in Ar under different temperature, and then using a flow of 5% H_2 during the temperature ramp. Based on the fact that bicarbonate, monodentate carbonate and carbonyl species could be desorbed at 120 °C, 170 °C and 450 °C respectively (see CO_2-TPD and DRIFTS), we set three purge temperature slightly higher (140 °C, 200 °C

or 500 °C) to provoke the desorption of targeted adsorbed CO_2 species. From the CO_2-TPSR results (Fig. 7c-7e), we can observe CH_4 formed from ca. 150 °C, and the CH_4 production profile is modified when altering the purge temperature. As expected, the total amount of CH_4 produced decreases when the purge temperature increases. After deconvoluting the CH_4 production profile, three distinct peaks centered at about 210 °C, 270 °C and 375 °C can be identified (denoted as P_{210}, P_{270}, and P_{375}). We hypothesize that these three methane production peaks may indicate different routes for CO_2 methanation starting from different adsorbed species.

The amount and percentage of CH_4 formed during TPSR for the different peaks are listed in Table S3. Comparing Fig. 7c (purge temperature: 140 °C) with Fig. 7d (purge temperature: 200 °C), a marked decrease of the P_{270} could be observed (while the other peaks are marginally modified). Since monodentate carbonate are the species that can be evacuated from the surface when the purge temperature increases from 140 °C to 200 °C, it can be inferred that the CH_4 from the P_{270} is related to the hydrogenation of monodentate carbonate. Since monodentate carbonate can be hydrogenated to CH_4 via the formate pathway with the monodentate formate as an intermediate[64], we propose that the P_{270} can be attributed to CH_4 formed via the formate pathway. Furthermore, an obvious decrease of the P_{210} is observed when comparing Fig. 7e (purge temperature: 500 °C) with Fig. 7d (purge temperature: 200 °C). Considering the fact that carbonyl species are desorbed when the purge temperature increases from 200 °C to 500 °C, the CH_4 from the P_{210} can be related to the hydrogenation of carbonyl. The carbonyl species can be hydrogenated to CH_4 via the RWGS+CO hydrogenation pathway.[50] Therefore, we propose the P_{210} can be attributed to the CH_4 formed via the RWGS+CO hydrogenation pathway.

DFT simulation was conducted to further investigate the possible reaction paths from CO_2 to CH_4. Although the metal-support interaction is a widely recognized effect in heterogeneous catalysis, using SiO_2, as an inert and stable support, could eliminate the impacts of oxygen vacancy and other factors (such as reduction-induced encapsulation) introduced by the support on the reaction.[68, 69] Furthermore, based on the

characterization, CO_2 adsorbed occurs solely on the surface of Ni, which allows us to simplify the structure of the catalysts to Ni, as typically needed in DFT studies.[70-72]

The reaction energy pathways for the hydrogenation of CO_2 into CH_4 over a model Ni (111) surface are given in Fig. 8. We find that the most endothermic step of RWGS+CO-hydrogenation pathway is the formation of methoxy ($*OCH_3$) at 156 kJ/mol, whereas for the formate pathway and C-O bond cleavage pathway, it is respectively the formation of the formate intermediate (*OCHO) at 174 kJ/mol and the formation of CH_4 from $*CH_3$ at 205 kJ/mol. Those three calculated energies are different but are in the same range, which means the corresponding pathway can potentially proceed in parallel. Our results show that the CO_2 methanation via RWGS+CO-hydrogenation pathway is lower in energy than that via formate pathway and C-O bond cleavage pathway; hence, RWGS+CO-hydrogenation pathway is more feasible and dominant at low temperature, in agreement with the TPSR results. Interestingly, we found a linear relationship between the temperatures of the three CH_4 formation peaks (TPSR) and the energy barrier of the RDS for each pathway obtained from DFT (Fig. 7f). Reasoning that P_{210} and P_{270} correspond to the CH_4 formed from the RWGS+CO and the formate pathways respectively, we propose that the P_{375} peak corresponds to methane production occurring via the C-O bond cleavage pathway. This can be consisted with the AP XPS data deported by Heine et al. [59], but it is suggested that further efforts are needed to provide direct experimental evidence for that pathway at high temperature.

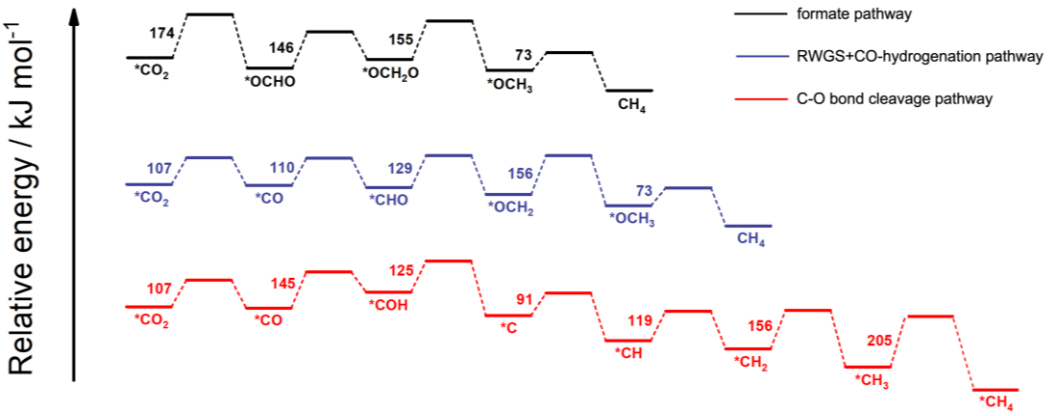


Fig. 8. Relative potential energy surfaces for CO_2 methanation in formate pathway, RWGS+CO-hydrogenation pathway and C-O bond cleavage pathway.

Overall, combining the experimental and theoretical methods, we identify that on the surface of the small Ni particles found in the high-loading Ni/SiO_2 catalysts, adsorbed CO_2 can be hydrogenated to CH_4 via three pathways. Monodentate carbonate can be hydrogenated to CH_4 in the formate pathway. Carbonyl from the dissociation of CO_2 and C from the further dissociation of CO on the catalyst surface are hydrogenated to CH_4 in RWGS+CO hydrogenation pathway and C-O bond cleavage pathway respectively. In the conditions of the continuous catalytic reaction, the co-existence and possible interplay of different mechanisms may explain why the Arrhenius plots features a broken line, with more than one activation energy. In particular, the inflection points (at ~ 250 °C) in the Arrhenius plots is between 210 °C and 270 °C (the temperature of first and second peak of deconvoluted TPSR curve), and the E_a below 250 °C is lower than the E_a over 250 °C, which suggests that the RWGS+CO hydrogenation pathway with lowest energy barrier is dominant below 250 °C. Theoretically, there should be another inflection points in the Arrhenius plots between 270 °C and 380 °C, but our study only includes data between 210 °C and 290 °C (in our set-up, it is difficult to reduce the CO_2 conversion to <15% when the reaction temperature is over 300 °C).

4. Conclusion

In summary, this study leads to two main conclusions. First, it is possible to prepare Ni/SiO_2 catalysts with high nickel loading, while maintaining high dispersion. Mesoporous Ni/SiO_2 catalysts were prepared using a simple sol-gel method. These catalysts exhibited high specific surface area (in the 350-530 m^2/g range), open texture and a high Ni dispersion (e.g., 11% for 38 wt.% Ni/SiO_2 catalyst) of small Ni nanoparticles (~4.6 nm). Consistently, these mesoporous Ni/SiO_2 catalysts displayed record specific activity (10.2 μmol g^{-1} s^{-1} at 250 °C), clearly outperforming other SiO_2 supported Ni-based catalysts.

Secondly, we provide insights into the CO_2 methanation mechanism that takes place on these catalysts. Combining theoretical and experimental methods, the occurrence of the three different CH_4 formation pathways can be confirmed. Carbonyl from the

dissociation of CO_2 is hydrogenated to CH_4 in the RWGS+CO hydrogenation pathway, which is dominant at low temperature (< 250 °C) due to its lowest energy barrier compared to the other two pathways. The formate pathway, correlated with the monodentate carbonate surface species, could proceed in parallel. C from the further dissociation of CO on the catalyst surface is hydrogenated to CH_4 in the C-O bond cleavage pathway.

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