



Short communication

Low temperature hybrid plasma-catalytic methanation over Ni-Ce-Zr hydrotalcite-derived catalysts



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ARTICLE INFO

Article history:

Received 10 February 2016

Received in revised form 20 April 2016

Accepted 26 April 2016

Available online 28 April 2016

Keywords:

CO₂-methanation

Plasma

Nickel catalysts

Hydrotalcites

ABSTRACT

The activity of Ceria and Zirconia-promoted Ni-containing hydrotalcite-derived catalysts was assayed in a hybrid plasma-catalytic process for the hydrogenation of carbon dioxide into methane at low temperatures and in the presence of a cold dielectric barrier discharge (DBD) plasma. High methane yields, around 80%, were measured under hybrid plasma-catalytic conditions, even at very low temperatures (110 °C, adiabatic conditions). In the absence of plasma, acceptably high CO₂ conversions and methane yields were only observed at temperatures higher than 330 °C. The presence of completely reduced Ni-crystallites of intermediate size, more readily available on the non-promoted catalysts was found to enhance the methanation reaction. Ce and Zr addition did not result in a noticeable improvement of the catalytic activity.

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1. Introduction

In the last decades, several strategies have been proposed in order to stabilize increasing atmospheric CO₂ concentrations [1]. Among them, CO₂ methanation, i.e. Sabatier reaction, is considered as one of the most effective technologies for CO₂ valorization, offering moreover a feasible route for renewable H₂ storage and utilisation [2,3]. Ni and Ni-Ru supported on diverse porous materials are typically used as catalysts in CO₂ methanation [2,4–6]. Ni-containing hydrotalcite-derived catalysts can be easily prepared through the incorporation of Ni-cations into their pristine brucite-like structure [7]. Such materials have already shown relatively high activity towards CO₂ methanation, at moderate temperatures, i.e. 350 °C [8]. Ce-species can be moreover ion-exchanged into such materials, resulting in an increased reducibility of the Ni-species, and in the introduction of intermediate strength basic sites (Lewis acid-base pairs), which can promote CO₂ adsorption and activate its hydrogenation [7]. The use of a Dielectric barrier discharge (DBD) plasma during the preparation of hydrotalcite-derived catalyst has lately shown to lead to the formation of relatively small Ni particles tightly bonded to the support which, in turn, facilitated the hydrogenation of CO₂ to CH₄ [9]. The in-situ use of cold DBD plasmas can furthermore assist the catalytic hydrogenation reaction through the formation of a large variety of active species, as has been recently reported for CO methanation [4,10].

In the present work, the CO₂ methanation activity of Ce and/or Zr-promoted Ni-Mg-Al hydrotalcite-derived catalysts was assayed in the absence and in the presence of a cold dielectric barrier discharge (DBD) plasma. With the aim of further modifying the basicity of HT-derived catalysts, Ce and Zr were added, either together with the Ni, Mg and Al precursors or, in the case of Ce, through ion exchange from a solution containing [Ce(EDTA)] – complexes.

2. Experimental

2.1. Catalysts synthesis

The Ni-containing Mg-Al hydrotalcites were synthesized through co-precipitation at constant pH from an aqueous solution containing Ni, Mg and Al nitrates (Mg/Ni = 3, M²⁺/M³⁺ = 3, 20 wt% Ni loading). Zirconium species were introduced into the hydrotalcite structure at the co-precipitation stage, using zirconium oxynitrate at molar ratio Al³⁺/Zr⁴⁺ equal to 9/1. Ce-species were introduced by ion exchange with a 3 wt% aqueous solution of [Ce(EDTA)] – complexes [7,11]. The resulting hydrotalcites were subsequently calcined at 550 °C for 4 h. Four different catalysts were prepared: HT-25Ni, Ce-promoted: HTNi-Ce, Zr-promoted: HTNi-Zr, and Ce-Zr-promoted: HTNi-CeZr. The X-ray fluorescence (XRF) analysis of the calcined catalyst confirmed the presence of 20 wt% Ni. The catalysts were reduced under 5 vol% H₂/Ar through temperature-programmed reduction (heating rate 5 °C/min) followed by isothermal reduction at 900 °C for 2 h.

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2.2. Physico-chemical characterization

The specific surface area (BET) of the materials was calculated from their respective N₂ adsorption isotherms acquired at −196 °C (degas: 150 °C, 4 h, BELSORP MINI II-BEL JAPAN). X-ray diffraction (XRD) patterns were recorded in an Empyrean diffractometer (PANalytical, CuKα source). Temperature-programmed reduction experiments (TPR, BEL Japan BELCAT-M, TCD detector) were performed under 25 mL/min of a 5 vol% H₂/Ar mixture (10 °C/min, 25–950 °C). CO₂-TPD experiments were carried out using 50 mg of reduced catalysts, pretreated for 1 h at 500 °C, then cooled down to 80 °C and fed with 10 vol% CO₂/He for 1 h. The catalysts was flushed with He for 20 min, then heated to 900 °C (10 °C/min).

2.3. Hybrid plasma-catalytic methanation

The activity of the different catalysts in CO₂-methanation was evaluated at temperatures from 110 to 430 °C, in a dielectric barrier discharge (DBD) plasma reactor operating at atmospheric pressure. It consisted of two coaxial tubes (quartz/alumina tubes), having internal diameters of 10 and 3 mm (2.5 mm gap), and 10 mm of effective length [11]. A high-voltage alternating current in the range of 14 kV (41 kHz) was applied in order to create DBD plasma, corresponding to a power between 3 and 9 W. Around 300 mg (0.6 cm³) of catalyst were placed at the annular space of the discharge zone in DBD reactor. A reactant gas containing 20 vol% CO₂ and 80 vol% H₂ was fed at 200 mL/min (GHSV = 20,000 h^{−1}). The gas temperature inside the catalytic bed was measured with the aid of a K-type thermocouple. The DBD plasma reactor was used either under adiabatic conditions or under isothermal conditions, using an electric furnace to reach the desired temperature in this last case. The gaseous products exiting the reactor were analyzed in a gas chromatograph (IGC-120-ML, Delsi Intersmat). CO₂ conversion (X_{CO₂}, %), CH₄ and CO selectivity (S_{CH₄} and S_{CO}, %), and CH₄ and CO yield (Y_{CH₄} and Y_{CO}, %), were calculated as follows:

$$X_{\text{CO}_2} = \frac{(n_{\text{CO}_2}^{\text{in}} - n_{\text{CO}_2}^{\text{out}})}{n_{\text{CO}_2}^{\text{in}}} \times 100 \quad (1)$$

$$S_{\text{CH}_4} = \frac{n_{\text{CH}_4}^{\text{out}}}{(n_{\text{CH}_4}^{\text{out}} + n_{\text{CO}}^{\text{out}})} \times 100 \quad (2)$$

$$Y_{\text{CH}_4} = X_{\text{CO}_2} \times S_{\text{CH}_4} \quad (3)$$

$$S_{\text{CO}} = \frac{n_{\text{CO}}^{\text{out}}}{(n_{\text{CH}_4}^{\text{out}} + n_{\text{CO}}^{\text{out}})} \times 100 \quad (4)$$

$$Y_{\text{CO}} = X_{\text{CO}_2} \times S_{\text{CO}} \quad (5)$$

A blank on-plasma test was performed in the absence of catalysts at 430 °C. This test yielded almost no CO₂ conversion and zero selectivity to CH₄. Off-plasma experiments were performed in the presence of each catalyst, at temperatures from 130 to 430 °C. The results of these off-plasma experiments are discussed in detail below.

3. Results and discussion

3.1. Characterization of the HTNi-derived catalysts

The XRD diffractograms acquired for the reduced HTNi-catalysts (Fig. not shown), evidence the typical reflections of hydrotalcite-derived mixed-oxides having a periclase-type structure (2θ: 43°, 62.5°; JCDSP00-045-0946) [12]. Several diffraction peaks corresponding to metallic nickel are as well present (2θ: 44°, 51°, 76°; JCDSP01-089-7128). In the case of Ce and/or Zr promoted catalysts, additional phases of segregated ceria (JCDSP00-043-1002) and/or zirconia (JCDSP00-049-

1642) can be observed. Ni crystal sizes were estimated using Scherrer equation and are presented in Table 1. Crystal size notably decreases as a consequence of the presence of Zr, i.e. from 20.7 nm in HTNi-Ce to 8.1 nm in HTNi-ZrCe. Table 1 shows as well the results of the textural characterization. The addition of Zr seems to increase the final porosity of the HT-derived mixed oxide, whereas Ce results in a certain extent of pore blockage, related to its incorporation through ion-exchange using [Ce(EDTA)][−] complexes.

The H₂-TPR profiles for these catalysts, Fig. 1, evidence a single wide and asymmetric reduction peak centered between 810 and 860 °C, arising from the reduction of nickel oxide in strong interaction with the Mg-Al mixed oxide matrix [7]. The shoulders appearing at about 600 °C can be assigned to segregated NiO-species, as already observed before [11]. For the Ce-promoted catalysts, i.e. HTNi-Ce and HTNi-ZrCe, the main reduction peak is shifted to lower temperatures, pointing to enhanced reducibility of Ni-species in the presence of this promoter. Additional reduction peaks at 300 and 415 °C arising from the reduction of Ce⁴⁺ to Ce³⁺ are also observed [7,13]. On the contrary, in the presence of Zr a shift to higher reduction temperatures can be observed, due to further stabilization and stronger interaction between the mixed Mg-Al oxides and Ni-species. H₂-TPR experiments were repeated after reduction of the catalysts at 900 °C for 2 h under 5 vol% H₂/Ar. Two small reduction peaks at much lower temperatures are now shown, i.e. at 172 and 250–300 °C, pointing to Ni or NiO segregation from the Mg-Al mixed oxide structure upon the reduction treatment [14] and further oxidized when storing the materials under ambient conditions. Bulk NiO is normally reduced at such low temperatures [15,16].

CO₂-TPD profiles for these reduced materials, Fig. 2, evidence the presence of three types of basic sites on the catalysts surface: (i) weak Brønsted OH-groups (ca. 120–130 °C), (ii) medium strength Lewis metal-oxygen pairs (175–235 °C), and (iii) strong Lewis-base oxygen anions (300–390 °C) [7,17,18]. The total basicity (Table 1) is remarkably influenced by the presence of Ce and/or Zr. The highest basicity corresponds to the CeZr-promoted catalyst, HTNi-CeZr. In general, the addition of both Ce and Zr results in an increased presence of medium-strength and strong basic sites, i.e. strong basic sites account for 50–51% of total basicity in HTNi-Ce and HTNi-Zr whereas they correspond to 85% of total basicity in HTNi-CeZr. Weak and medium strength basic sites contribute to more than 75% of the total basicity in HTNi.

3.2. Activity towards methanation in the absence of plasma (off-plasma experiments)

The results of the off-plasma methanation experiments are shown in Fig. 3, in the presence of the four different catalysts and at temperatures from 130 to 430 °C. In the absence of the DBD plasma, CO₂ conversion only becomes significant at temperatures higher than 320 °C. It increases rapidly with increasing temperature, tending towards the thermodynamically forecasted values [19,20]. The non-promoted catalyst, HTNi, shows the highest off-plasma activity within this series of catalysts. The addition of Ce results in much lower activity and selectivity towards the production of methane, with CO yields reaching almost 7% (Fig. not shown). Off-plasma activity seems to be directly related to the size and availability of Ni⁰ particles on the catalyst's surface. The

Table 1
Basicity (CO₂-TPD), Ni-crystal size (XRD), and textural properties for the HT-derived catalysts.

Catalyst	Total basicity [mmol/g]*	Ni crystallite size [nm]**	S _{BET} [m ² /g]	V _{total} [cm ³ /g]
HTNi	0.060	15.2	115	0.41
HTNi-Ce	0.094	20.7	102	0.33
HTNi-Zr	0.064	10.5	229	0.62
HTNi-ZrCe	0.119	8.1	158	0.56

* calculated from CO₂ TPD.

** calculated from Scherrer Equation (XRD).

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