Integrated carbon capture and utilization: Synergistic catalysis between highly dispersed Ni clusters and ceria oxygen vacancies

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**Keywords:** Sub-nanometer catalysts, Oxygen vacancies, Carbon capture, Methane, CeO$_2$

**Abstract**

Integrated carbon capture and utilization (ICCU) presents an ideal solution to address anthropogenic carbon dioxide (CO$_2$) emissions from industry and energy sectors, facilitating CO$_2$ capture and subsequent utilization through conversion into high-value chemicals, as opposed to current release into the atmosphere. Herein, we report the synergistic coupling of porous CaO, as a sorbent for CO$_2$ capture, and Ni doped CeO$_2$ nanorods, as catalytic sites for CO$_2$ reduction. It is found that ceria is shown to possess the capacity for CO$_2$ utilization, however, critically it only results in the generation of CO due to the weak CO-ceria bonding. The addition of Ni active sites gives rise to CH$_4$ being the predominant product, via the strong interaction between Ni species and CO, which facilitates further reduction. Through tuning Ni loadings, we have evaluated the role of catalytic active site size, with a Ni loading of only 0.5 wt% providing optimal performance through the formation of sub-nanometer sized clusters. This near-atomic active site dispersion gives rise to CH$_4$ productivity and selectivity of 1540 mmol g$^{-1}$ Ni and 85.8%, respectively, with this optimal combination of catalyst and sorbent demonstrating high stability over 10 cycles of ICCU process. These observations in parallel with the synergistic coupling of Earth-abundant, low-cost materials (CaO and Ni) will have broad implications on the design and implementation of high efficiency, cost-effective ICCU materials and processes.

**1. Introduction**

Atmospheric carbon dioxide (CO$_2$) concentrations have undergone extraordinary increases from 310 to 416 ppm in the past half-century primarily because of fossil fuel combustion [1–3]. Carbon capture and utilization (CCU) has drawn intensive interest due to its capacity to sequester CO$_2$ and utilise it as a source of carbon to produce high-value chemicals and fuels, and thus promote a circular economy while mitigating against climate change [4,5]. However, state-of-the-art CCU exhibits poor economics and technological complexity due to extensive energy input, a multiple reactor configuration, and sorbent transfer between reactors, to allow temperature or pressure swing sorbent regeneration [6,7]. Recently, promising integrated carbon capture and utilization (ICCU) has emerged as a lower-cost alternative technology, with captured CO$_2$ converted into value-added products, e.g. CO and CH$_4$, within a single reactor under isothermal conditions [8,9]. During ICCU, two steps are involved: 1$^{\text{st}}$ step is carbon capture from flue gas using an adsorbent, subsequently the captured CO$_2$ is rapidly converted over catalytic sites in the 2$^{\text{nd}}$ step [10–14]. The integration of these steps offers potential improvements in efficiency and cost-effectiveness, while

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allowing a one reactor process under isothermal conditions. Thus, the development of materials and systems that can capture CO\textsubscript{2} and facilitate its conversion to other high-value chemicals at the same temperature is highly desirable [15,16].

CaO is regarded as a promising carbon capture material due to its high theoretical CO\textsubscript{2} uptake of 17.8 mmol g\textsuperscript{-1} and low cost [17–19]. Duyar et al. employed nano-dispersed CaO on alumina, produced via simple wet impregnation, as the sorbent [9], whilst Arellano-Treviño et al. investigated alkaline and alkaline earth oxides as sorbents, identifying CaO to be a reasonable sorbent candidate [13]. Noble metals, specifically Ru [9,13] and Rh [20], supported over high surface area oxide such as Al\textsubscript{2}O\textsubscript{3} are commonly deployed as catalysts because of their high activity and selectivity in CO\textsubscript{2} conversion to CH\textsubscript{4}. Ru based systems have been reported by Duyar and co-workers, and Bermejo-López et al. [9,12], both coupled with CaO sorbent in dual functional materials, in which catalysts and sorbent were deposited on a single support, for isotherm capture and conversion. While Bermejo reported an optimal methane production of 414 μmol g\textsuperscript{-1} at 400 °C, Duyar show excellent stability at 320 °C over 11 capture and conversion cycles (average methane production 283 μmol g\textsuperscript{-1}). Unfortunately, the high cost of noble metals and potential poor resistance to pollutants are drawbacks that may hinder their widespread deployment [21]. Earth-abundant metals, such as nickel, are promising alternative catalytic sites for ICCU, due to cost-effectiveness, and critically that they enable a temperature window for catalysis which is compatible to that required for CO\textsubscript{2} capture [22,23]. However, Arellano-Treviño et al. observed that at lower ICCU process temperature (320 °C), Ni-based catalyst sites were not reduced to the active state, resulting in poor performance compared to Ru or Rh [13]. Thus, catalysts and process conditions require further development for efficient and cost-effective ICCU to be realised.

Active site miniaturisation provides a route to enhance catalytic performance through escalating active site density. Theoretical and experimental studies have revealed the prospect of sub-nanometer metallic active sites, offering superior catalytic activity and selectivity [24,25], while maximizing the efficiency of metal utilization, and fine-tuning active site environmental structure [26]. However, highly dispersed metal sites can display high mobility at elevated temperatures, leading to agglomeration due to their high surface energy [27]. Addressing the above challenges, downsizing metallic catalytic sites to sub-nanometer scale while anchoring them on the supports is highly desirable and critical to efficient and cost-effective ICCU processes [28]. Among various metal oxides, e.g. Al\textsubscript{2}O\textsubscript{3}, SiO\textsubscript{2}, and TiO\textsubscript{2} used as supports in methanation catalysis, CeO\textsubscript{2} has drawn intensive attention due to its basic nature, high stability, and capacity for oxygen vacancy formation [29,30]. These vacancies can directly dissociate CO\textsubscript{2} to CO\textsuperscript{*}, and thus provide a pathway to initiate and enhance CO\textsubscript{2} conversion [8,31], while a high affinity between surface lattice oxygen and metal atoms can stabilize guest cations, maintaining high metal dispersion on CeO\textsubscript{2} support [32]. However, a detailed understanding of such interaction between highly dispersed metal clusters sites and CeO\textsubscript{2} support sites is lacking, as is insight into the reaction mechanism. This absence of knowledge retards the rational design of efficient materials utilized in the ICCU process, and therefore addressing these deficiencies in knowledge is paramount.

Herein we report the synthesis of effective materials for capture (CaO sorbents) and utilisation (sub-nanometer Ni doped CeO\textsubscript{2} nanorods), and their combination as a physical mixture used in the ICCU process for methane production. The process, depicted in Scheme 1, comprises a capture cycle, in which CO\textsubscript{2} from flue gas is adsorbed by CaO to produce CaCO\textsubscript{3}, under the subsequent utilisation cycle, in which gas feed switch to a hydrogen-rich stream, the captured CO\textsubscript{2} was converted into methane over Ni/CeO\textsubscript{2} catalyst.

2. Experimental

2.1. Preparation of catalysts

A hydrothermal process, as previously reported, was used to synthesize CeO\textsubscript{2} nanorods [33]. Typically, 1.730 g cerium nitrate hexahydrate (Ce(NO\textsubscript{3})\textsubscript{2}-6H\textsubscript{2}O) and 20.0 g of sodium hydroxide (NaOH) were dissolved in 10 mL and 70 mL of deionized water to get the solution A and B, respectively. The mixture obtained by adding solution A into solution B was stirred for 30 min at room temperature, and then transferred into a stainless-steel autoclave (100 mL) and maintained at 100 °C for 24 h. After cooling down to room temperature, the products were separated by centrifugation and then washed with water until the pH reached 7 and dried at 80 °C overnight to obtain CeO\textsubscript{2} nanorods.

A wet impregnation method was used to prepare CeO\textsubscript{2} supported catalysts. Typically, a predetermined amount of nickel nitrate hexahydrate Ni(NO\textsubscript{3})\textsubscript{2}-6H\textsubscript{2}O, corresponding to 0.5 wt%, 1 wt% and 5 wt% of Ni was dissolved into 16 mL deionized water and then 0.8 g CeO\textsubscript{2} nanorods were added. The mixture solution was stirred at room temperature for 8 h, before the evaporation of water at 80 °C and then dried overnight. The samples were reduced at 550 °C in 5% H\textsubscript{2}/N\textsubscript{2} for 3 h at a heating rate of 2 °C min\textsuperscript{-1}, and are identified as 0.5%Ni/CeO\textsubscript{2}, 1%Ni/CeO\textsubscript{2} and 5%Ni/CeO\textsubscript{2}, respectively. When the heating rate increased to 10 °C min\textsuperscript{-1}, the catalyst is designated 5%Ni/CeO\textsubscript{2}-10. The reduction temperature was determined by H\textsubscript{2}-TPR of the synthesized materials (isolated before reduction), as shown in Fig. S1, with nickel nitrate fully reduced below 550 °C. H\textsubscript{2}-TPR was carried out on VDSorb-91i purchased from Quzhou.

![Scheme 1. Schematic illustrating the role of CaO sorbent and highly dispersed Ni clusters supported on CeO\textsubscript{2} nanorods during ICCU.](image-url)
The loadings were determined by an inductively coupled plasma optical emission spectrometry (ICP-OES, Agilent 720). High-resolution transmission electron microscopy (HRTEM) and high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) measurements coupled with EDX were performed on a TALOS F200X G2 microscope, operating at an acceleration voltage of 200 kV. Powder samples were prepared for imaging by dispersing in methanol and deposited to dry holey carbon grids.

Powder X-ray diffraction (XRD) patterns ranging from 10 to 80° were collected by a PANalytical empyrean series 2 diffractometer with Cu Ka X-ray source. XRD data were analysed by X’pert Highscore plus software.

X-ray absorption spectroscopy (XAS) at Ni K-edge (8.3 keV) were recorded at the B18 beamline of the Diamond Light Source, UK, using Si (111) double crystal monochromator. The catalysts were pelleted with boron nitride. All samples were collected in fluorescence mode, while standards were collected in transmission. Ni foil spectra were simultaneously collected to samples and standards to enable energy calibrations. Data processing was carried out using Demeter open source software package, version 0.9.26, with XAS spectra processing (normalization and background subtractions) and extended X-ray absorption fine structure (EXAFS) fitting conducted within the Athena and Artemis programs, respectively.

XPS data were acquired using a Kratos Axis SUPER using monochromated Al Kα (1486.69 eV) X-rays at 12 mA emission and 15 kV HT (180 W) and a spot size/analysis area of 700 × 300 μm. The instrument was calibrated to gold metal Au 4f (83.95 eV) and dispersion adjusted to give a BE of 932.6 eV for the Cu 2p3/2 line of metallic copper. Ag 3d5/2 line FWHM at 10 eV pass energy was 0.544 eV. Source resolution for Vodo Instrument Co. Ltd. 100 mg of synthesized catalyst was placed into a U-shape tube and pre-treated at 100 °C for 30 min in pure N2. After cooling to 50 °C, H2-TPR was conducted under 5% H2/N2 (30 mL min⁻¹) at a heating rate of 10 °C min⁻¹ up to 800 °C.

2.2. Preparation of adsorbent

A standard sol–gel process proposed by Santos et al. was used to synthesize a CaO adsorbent [34]. A predetermined amount of calcium nitrate tetrahydrate (Ca(NO3)2·4H2O) and citric acid monohydrate (C6H5O7·H2O) acting as chelation agent, were added to the deionized water at room temperature (water and citric acid to metal ion molar ratios were 40:1 and 1:1, respectively). The mixture was continuously stirred at 80 °C to form a translucent pale-yellow sol with good dispersion. After drying the prepared sol overnight at 130 °C, the translucent pale-yellow sol turned into low-density foam. The obtained foam was then calcined in a muffle furnace at 850 °C for 2 h at a heating rate of 2 °C min⁻¹. This synthesized sample was designated as sol–gel CaO. A detailed investigation into the CaO adsorbent, including extensive characterisation and the carbonation mechanism can be found in our previous publication [35].

2.3. Material characterizations

The Ni loadings were determined by an inductively coupled plasma optical emission spectrometry (ICP-OES, Agilent 720). High-resolution transmission electron microscopy (HRTEM) and high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) measurements coupled with EDX were performed on a TALOS F200X G2 microscope, operating at an acceleration voltage of 200 kV. Powder samples were prepared for imaging by dispersing in methanol and deposited to dry holey carbon grids.

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Carbon balance = \( \frac{\text{CH}_4 \text{ yield} + \text{CO}_2 \text{ yield} + \text{CO yield}}{\text{CO}_2 \text{ capture capacity}} \)  

CO conversion = \( \frac{\text{CH}_4 \text{ yield} + \text{CO yield}}{\text{CO}_2 \text{ capture capacity}} \)
\[ \text{CH}_4 \text{ selectivity} = \frac{\text{CH}_4 \text{ yield}}{\text{CH}_4 \text{ yield} + \text{CO yield}} \]  

(3)

2.5. DFT calculations

DFT calculations were carried out with a periodic plane wave using the Vienna ab initio simulation package (VASP) [38]. The exchange–correlation potentials were described within the generalized gradient approximation (GGA) in the form of Perdew-Burke-Ernzerhof (PBE) [39]. The projector augmented wave (PAW) method was utilized to describe the electron–ion interactions [40]. During the structure relaxation, the convergence criterion was set to 0.03 eV/Å and 10\(^{-5}\) eV for the residual force and energy, respectively. A \(2 \times 3\) supercell of \(\text{CeO}_2\) (1 1 0) with an oxygen vacancy was used as the \(\text{CeO}_2\) substrate. The Brillouin zones were sampled by a \(3 \times 3 \times 1\) Monkhorst-Pack k-point mesh. To avoid the interaction between two periodic units, a vacuum space of 15 Å was employed.

The adsorption energy of CO was calculated by:

\[ E_b = E_{\text{CO}}^* - E_r - E_{\text{CO}} \]  

(4)

Where \(E_{\text{CO}}^*\) and \(E_r\) are the energies of systems with and without the adsorption of CO, and the \(E_{\text{CO}}\) is the energy of a CO molecule in the gas phase. Therefore, a more negative \(E_b\) indicates a stronger adsorption strength of CO.

3. Results and discussion

3.1. Characterisation of sorbent and catalysts

The structure of CaO sorbent and pristine \(\text{CeO}_2\) were examined by TEM, as presented in Fig. S3. The porous structure of CaO sorbents is confirmed in Fig. S3a, which is in agreement with the literature and results from the addition of citric acid to the sol–gel method [34]. This material has previously demonstrated excellent performance for carbon capture [41,42]. The \(\text{CeO}_2\) support presents as nanorods with a width and length spanning 10 to 20 nm and 100 to 200 nm, respectively, as shown in Fig. S3b, which concurs with the originally reported synthesis [33]. The support morphology and highly crystalline nature are unaffected by Ni doping as shown in Fig. 1, with an interplanar spacing of 0.19 nm attributed to the \(\text{CeO}_2\) (1 1 0) phase, present for all Ni loadings.

ICP-OES results (Table 2) show Ni loadings are 0.3 wt%, 0.6 wt%, 3.8 wt% and 3.7 wt% in 0.5\%Ni/\(\text{CeO}_2\), 1\%Ni/\(\text{CeO}_2\), 5\%Ni/\(\text{CeO}_2\) and 5\%Ni/\(\text{CeO}_2\)-10, respectively. The numbers are slightly lower than the theoretical values. This is because the samples were prepared by the impregnation method and ICP is used to determine the Ni content of the bulk phase. STEM-EDX elemental mapping was applied to determine the distribution of Ni within the synthesized catalysts. A uniform Ni elemental distribution in both 0.5\%Ni/\(\text{CeO}_2\) (Fig. 1c) and 1\%Ni/\(\text{CeO}_2\) (Fig. 1f) confirms that NiO is well dispersed on the \(\text{CeO}_2\) nanorod substrate. Further increasing Ni loading to 5 wt%, the interplanar spacing of 0.21 nm is observed in Fig. 1g, which is corresponding to NiO (2 0 0) lattice plane. In addition, a more concentrated Ni elemental distribution is shown in 5\%Ni/\(\text{CeO}_2\) (Fig. 1i) indicating the formation of large NiO nanoparticles. A further increase in NiO size was observed when the reduction ramp rate was increased to 10 °C min\(^{-1}\) (Fig. S4). Thus, to obtain highly dispersed sub-nanometer Ni active sites, Ni loading and catalyst processing are critical, with the latter facilitating the slower formation and desorption of water in combination with stabilization of mobile Ni species [43].

XRD results in Fig. 2a show eight diffraction peaks at 28.5°, 33.2°, 47.6°, 56.5°, 59.2°, 69.4°, 76.7° and 79.1°, indicating a cubic fluorite structure of \(\text{CeO}_2\) (JCPDS 34–0394), and indexed to (1 1 1), (2 0 0), (2 2 0), (3 1 1), (2 2 2), (4 0 0), (3 3 1) and (4 2 0) planes, respectively [44]. After introducing Ni on the surface of \(\text{CeO}_2\) nanorods, the support crystal structure was unchanged, with no apparent Ni-containing crystal phases were detected due to the insensitivity of X-ray diffraction to small clusters [45]. This bulk analysis is in good agreement with the localised electron microscopy interpretation. The zoom area of XRD spectra

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**Increasing Ni contents**

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**Fig. 1.** HRTEM, HAADF-STEM images and EDX elemental mappings of (a-c) 0.5\%Ni/\(\text{CeO}_2\); (d-f) 1\%Ni/\(\text{CeO}_2\) and (g-i) 5\%Ni/\(\text{CeO}_2\).
ranging from 25 to 35° is shown in Fig. S5. It is found that the peak positions attributed to CeO$_2$ shifted to a higher angle after introducing of Ni species, which indicates a lattice contraction of Ni/CeO$_2$ catalysts. To further verify the local structures of the CeO$_2$ nanorod supported Ni clusters, Ni K-edge XAS was conducted. Edge position and X-ray absorption near-edge spectra (XANES) as shown in Fig. 2b reveal Ni to be present in the +2 oxidation state as NiO for all loadings [46]. Fig. 2c and 2d show the K-space EXAFS spectra and corresponding Fourier Transform, and illustrate a good agreement between fit and raw data. The Fourier Transform of the EXAFS spectra confirm the oxidic nature of the Ni phase in all catalysts as identified by XANES, with major contributions from Ni-O and Ni-Ni (oxide 2nd shell) at 2.0 and 2.9 Å, respectively in Table 1. Furthermore, the absence of a significant scatter at 2.5 Å rules out the presence of Ni-Ni scatter from a metallic phase. EXAFS fitting confirms the lack of metallic Ni-Ni scatters in 0.5%Ni/CeO$_2$ and 5%Ni/CeO$_2$, with an increased contribution from a second shell NiO scatters in 5%Ni/CeO$_2$, reflecting an increase in NiO cluster size. Average NiO particle size from 1st shell CN are calculated to be 0.8 and 1.8 nm for 0.5%Ni/CeO$_2$ and 5%Ni/CeO$_2$, respectively [47], reflecting the same trend observed by electron microscopy. In contrast, fitting of 5%Ni/CeO$_2$ is significantly improved with the addition of a metallic Ni 1st shell scatter, indicating a degree of metallic Ni, albeit very minimal (coordination number of 1.9). We propose this indicates a metal-core oxide-shell structure, reflecting a further increase in Ni cluster size.

As reported in the literature, the peak centred at 466 cm$^{-1}$ is assigned to the F$_{2g}$ vibration mode of CeO$_2$ with fluorite structure [48]. The two weaker bands at 598 cm$^{-1}$ and 1174 cm$^{-1}$ corresponded to the defect-induced (D) vibrational mode from oxygen vacancies and the second-order longitudinal mode in CeO$_2$ lattice, respectively [49]. Therefore, Raman spectroscopy has been reported to probe surface electronic states and structural defects. Relative concentration of oxygen vacancies can be quantified from the intensity ratio of $I_D/I_{F_{2g}}$. The

Table 1

<table>
<thead>
<tr>
<th>Sample</th>
<th>Ni foil</th>
<th>0.5%Ni/CeO$_2$</th>
<th>5%Ni/ CeO$_2$</th>
<th>5%Ni/ CeO$_2$-10</th>
</tr>
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<tr>
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<td>Ni (metal)</td>
<td>Ni (oxide)</td>
<td>O (oxide)</td>
</tr>
<tr>
<td>Ni foil</td>
<td>N/A</td>
<td>12.0</td>
<td>N/A</td>
<td>6.0</td>
</tr>
<tr>
<td>NiO</td>
<td>6.0</td>
<td>N/A</td>
<td>12.0</td>
<td>N/A</td>
</tr>
<tr>
<td>0.5%Ni/CeO$_2$</td>
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<td>0.0</td>
<td>7.1</td>
<td>0.0</td>
</tr>
<tr>
<td>5%Ni/ CeO$_2$</td>
<td>3.9</td>
<td>0.0</td>
<td>9.6</td>
<td>0.0</td>
</tr>
<tr>
<td>5%Ni/ CeO$_2$-10</td>
<td>4.8</td>
<td>1.9</td>
<td>9.5</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Fig. 2. (a) XRD patterns, (b) Normalized XANES spectra, (c) K-space EXAFS spectra, (d) $k^3$-weighted Fourier Transform EXAFS spectra.
Raman spectra of pristine CeO$_2$ and Ni/CeO$_2$ catalysts are shown in Fig. S6. It is found that the peak at 466 cm$^{-1}$ exhibits a red shift in all the Ni/CeO$_2$ catalysts indicating a degree of Ni species incorporation within the ceria lattice [50]. However, the peaks at 598 cm$^{-1}$ and 1174 cm$^{-1}$ are not obvious as expected in our Raman spectra. Therefore further characterizations should be conducted to confirm the variation of oxygen vacancies.

XPS analysis was used to investigate the CeO$_2$ supported catalysts’ surface characteristics, as displayed in Fig. 3a-d. Ce 3d peaks were fit using a Shirley background and a cross-section of (1150.84, -450, 0, 0) according to the model of Romeo et al. [37]. The Ce$^{3+}$/Ce$^{4+}$ ratio was determined through integration of the peak model wherein Ce$^{4+}$ is represented by 6 peaks (v, v', v'', u, u' and u'') centred at 882.2, 888.4, 897.8, 900.3, 907.7 and 916.4 eV, respectively) and Ce$^{3+}$ is represented by 4 peaks (v', u, u' centred at 880.3, 884.3, 898.3 and 902.5 eV, respectively) [51]. The resultant ratios agree with that of the Raman spectra, in that the number of vacancies increases with increased Ni loading up to Ni 1%, before decreasing again with increased Ni loading, though remaining higher in number than that of the bare ceria as summarized in Table 2. The increase in vacancies upon the addition of Ni is due to a metal-oxide charge transfer from the nickel 4s orbitals into the empty Ce 4f band, which reduces Ce$^{4+}$ sites to Ce$^{3+}$ sites [52]. The decrease in the number of vacancies at higher loadings may be attributed to the growth mode of Ni on CeO$_2$ and subsequent attenuation of the signal from Ce$^{3+}$ regions relative to Ce$^{4+}$ region by the small Ni clusters (which by the nature of Ni-CeO$_2$ interactions will tend to form over Ce$^{3+}$ sites). Ni on CeO$_2$ has been known to form 2D-like structures at lower loadings before forming 3D clusters after a critical point, due to

Table 2

<table>
<thead>
<tr>
<th>Sample</th>
<th>Ni loading$^a$</th>
<th>Ni dispersion$^b$</th>
<th>Ce 3d Ce$^{3+}$/Ce$^{4+}$</th>
<th>O 1s O$_V$/O$_L$</th>
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<td>CeO$_2$</td>
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<td>0.69</td>
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<td>0.5%Ni/CeO$_2$</td>
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<td>0.82</td>
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<tr>
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<td>0.35</td>
<td>1.14</td>
</tr>
<tr>
<td>5%Ni/CeO$_2$</td>
<td>3.8</td>
<td>30</td>
<td>0.29</td>
<td>0.89</td>
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<tr>
<td>5%Ni/CeO$_2-10$</td>
<td>3.7</td>
<td>29</td>
<td>/</td>
<td>/</td>
</tr>
</tbody>
</table>

$^a$ Ni loading is determined by ICP.  
$^b$ Ni dispersion obtained from CO chemisorption.

the strong interaction between Ni and CeO$_2$ causing significant wetting [53]. Once the formation of 3D particles begins, the increase in the number of new vacancy sites will cease to increase proportionally with Ni loading, and hence attenuation effects of Ce$^{3+}$ 3d electrons will reduce the effective concentration.

Analysis of the Ni 2p regions is complicated by the presence of some high energy structure from the Ce LMM auger which introduces difficulty in correctly modelling the background, particularly for the materials of a lower Ni loading. To compensate for this, a model Ce LMM background was developed by measuring the blank ceria across the energy range of the Ni 2p and used to correct the spectra in which Ni 2p and Ce LMM produced competing intensity (Fig. S7). Analysis of the raw, unaltered data appeared to suggest that the Ni was present solely as relatively large NiO clusters, exhibiting both the standard Ni$^{2+}$ photo-emission core line peak and the associated NiO$_6$ inter-cluster. However, when the contribution from the Ce LMM auger was removed via a

Fig. 3. (a) Ce 3d XPS spectra: blue profiles Ce$^{4+}$ envelopes, red profiles Ce$^{3+}$ envelopes, (b) Quantified Ce(III) % as a function of Ni loading, (c) Ni 2p XPS spectra and peak fitting curves following a SG-Quadratic auger subtraction process (Green-GS multiplet approximation of Ni$^{2+}$ free ion [36], Blue-cd$^{10}$L$^2$ final-state satellite, Red-unscreened cd$^8$ core-line) and (d) cd$^{10}$L$^2$ contribution as a function of Ni loading. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
spectral subtraction method, the satellite intensity was altered and two states at +7 eV and +10 eV appeared. The +7 eV satellite is commonly observed in clusters of multiple NiO₆ centres and can be attributed to the screening process of final state cd₁₀ L₂ [54], while the highest energy peak may be attributed to the unscreened cd₈ final state [55].

Four methods of background subtraction were performed as displayed in Fig. S8: (1) using the raw data from the Ni 2p region of the blank ceria (Fig. S9) following a Savitzky-Golay quadratic smoothing process and smoothing width of 17, (2) following a Gaussian smoothing process and smoothing width of 17, (3) developed using the resultant envelope from a component fit of the entire Ce LMM region, and (4) using a background trace from a Shirley-type background across the Ni 2p energy region (Fig. S10). We found good agreement between the different approaches, with only the S-type background trace reporting a higher proportion of the cd₁₀ L₂ final-state, as shown in Fig. S11. Averages and standard deviations reported a general trend suggesting that as we move towards smaller clusters with decreasing Ni loading, the intensity from the cd₁₀ L₂ final-state satellite decreases, which we attribute to the reduction in Ni coordination number as we approach sub-nanometer sizes, as indicated by the XAS measurements.

O 1 s regions as shown in Fig. S12 further confirm the presence of oxygen vacancies in the synthesized catalysts. The peaks at around 528.9 and 530.2 eV are assigned to the lattice oxygen (O₃) and oxygen deficient regions (Oᵥ), respectively [48,56,57]. The ratio of Oᵥ/O₃ as shown in Table 2 is calculated to represent the abundance of oxygen vacancies in CeO₂-based catalysts. These values are 0.69, 0.82, 1.14 and 0.89 for pristine CeO₂, 0.5%Ni/CeO₂, 1%Ni/CeO₂, and 5%Ni/CeO₂, respectively. The results show that 1%Ni/CeO₂ has the most abundant

![Fig. 4. (a, b) ICCU performance, (c, d) cyclic ICCU performance of 0.5%Ni/CeO₂-CaO. (e) the comparison of ICCU performance between this study and reported in the literature, (f) the enlarged view of blue area in Fig. 4e. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)](image-url)
3.2. ICCU performance of materials

The ICCU performance of the physical mixture of CaO and sub-nanometer Ni cluster supported on ceria nanorods were evaluated at 550 °C and 1 bar. The results are presented in Fig. 4 and Table 3. When the nickel-free CeO$_2$-CaO combination is used, a carbon capture capacity of 14.9 mmol g$^{-1}$ is achieved, and CO is the sole product in the utilization step. This partial reduction occurs over oxygen vacancies within the ceria, which absorb CO$_2$ and promote C-O bond cleavage through the oxidation of CeO$_2$ support as shown in Eq. (5) [8], with hydrogen reactivating the catalytic sites (Eq. (6)). The carbon balance and CO$_2$ conversion of CeO$_2$-CaO are only 48.5% and 39.5%, respectively (Fig. 4b). The obtained low carbon balance is accounted for the incomplete desorption of CO$_2$ from the adsorbent, shown by CaCO$_3$ content in Fig. S13. This observation agrees with the literature, which identified low activity but high selectivity for CO$_2$ conversion and CH$_4$ yield using 0.5%Ni/CeO$_2$-CaO after 10 cycles of ICCU process at 550 °C, respectively. The initial CH$_4$ yield of 0.5%Ni/CeO$_2$-CaO after the 1st cycle of ICCU process is 7.9 mmol gcat.$^{-1}$ and the CO$_2$ conversion and CH$_4$ selectivity are 51.0% and 86.2%, respectively. After 10 cycles of the ICCU process, even though the CH$_4$ yield is decreased to 5.2 mmol gcat.$^{-1}$, the CO$_2$ conversion and CH$_4$ selectivity are still as high as 53.5% and 78.4%, respectively, which indicate that the sub-nanometer catalysts exhibited a good stability. Through the comparison of ICCU performance after 10 cycles, the CO$_2$ conversion using 0.5%Ni/CeO$_2$-CaO is 53.5% which is higher than 1%Ni/CeO$_2$-CaO (50.4%). This is attributed to the high Ce$^{3+}$/Ce$^{4+}$ ratio of 0.5%Ni/CeO$_2$-CaO (0.30), while 1%Ni/CeO$_2$-CaO has a Ce$^{3+}$/Ce$^{4+}$ ratio of 0.24, as shown in Fig. S15, further implying that the oxygen vacancies are important for the conversion of captured CO$_2$ during the ICCU process. In addition, XPS of spent materials reveal a nickel state which is hydroxidic in nature (Fig. S16), as evidenced by subtle shifts to a higher binding energy, accompanied by a significant decrease in the satellite structure at ~3+ and ~7+ eV compared with the oxide fresh material [59]. Moreover, both the spent 0.5%Ni/CeO$_2$-CaO and 1%Ni/CeO$_2$-CaO displayed an obvious peak centered at 700 °C as shown in Fig. S17, which is attributed to decomposition of CaCO$_3$, further indicating the incomplete desorption of CO$_2$ from the adsorbent. However, we do not find any peaks assigned to the coke deposition because the coke always be burned below 600 °C. Therefore, the deactivation of the physical mixing materials during the ICCU process might be attributed to the sintering of sorbents because the capacity of carbon capture is decreased from 18.0 mmol g$^{-1}$ to 12.4 mmol g$^{-1}$ after 10 cycles of the ICCU process.

The cyclic stability, in particular at elevated temperatures, is crucial for the industrial application of sub-nanometer catalysts in the ICCU process. Fig. 4c and d, as well as Fig. S14 show the stability of 0.5%Ni/CeO$_2$-CaO and 1%Ni/CeO$_2$-CaO after 10 cycles of ICCU process at 550 °C, respectively. The initial CH$_4$ yield of 0.5%Ni/CeO$_2$-CaO after the 1st cycle of ICCU process is 7.9 mmol gcat.$^{-1}$ and the CO$_2$ conversion and CH$_4$ selectivity are 51.0% and 86.2%, respectively. After 10 cycles of the ICCU process, even though the CH$_4$ yield is decreased to 5.2 mmol gcat.$^{-1}$, the CO$_2$ conversion and CH$_4$ selectivity are still as high as 53.5% and 78.4%, respectively, which indicate that the sub-nanometer catalysts exhibited a good stability. Through the comparison of ICCU performance after 10 cycles, the CO$_2$ conversion using 0.5%Ni/CeO$_2$-CaO is 53.5% which is higher than 1%Ni/CeO$_2$-CaO (50.4%). This is attributed to the high Ce$^{3+}$/Ce$^{4+}$ ratio of 0.5%Ni/CeO$_2$-CaO (0.30), while 1%Ni/CeO$_2$-CaO has a Ce$^{3+}$/Ce$^{4+}$ ratio of 0.24, as shown in Fig. S15, further implying that the oxygen vacancies are important for the conversion of captured CO$_2$ during the ICCU process. In addition, XPS of spent materials reveal a nickel state which is hydroxidic in nature (Fig. S16), as evidenced by subtle shifts to a higher binding energy, accompanied by a significant decrease in the satellite structure at ~3+ and ~7+ eV compared with the oxide fresh material [59]. Moreover, both the spent 0.5%Ni/CeO$_2$-CaO and 1%Ni/CeO$_2$-CaO displayed an obvious peak centered at 700 °C as shown in Fig. S17, which is attributed to decomposition of CaCO$_3$, further indicating the incomplete desorption of CO$_2$ from the adsorbent. However, we do not find any peaks assigned to the coke deposition because the coke always be burned below 600 °C. Therefore, the deactivation of the physical mixing materials during the ICCU process might be attributed to the sintering of sorbents because the capacity of carbon capture is decreased from 18.0 mmol g$^{-1}$ to 12.4 mmol g$^{-1}$ after 10 cycles of the ICCU process.

The in-situ DRIFTS study was used to investigate the interaction between highly dispersed Ni clusters and oxygen vacancies over Ni/CeO$_2$ sub-nanometer catalysts. After introducing CO$_2$ (1st stage of ICCU), the IR bands centered at 2326, 2360, 3597, 3631, 3698 and 3734 cm$^{-1}$ come out immediately as shown in Fig. 5a, indicating the adsorption of gas-phase CO$_2$ [60,61]. In addition, the IR features developed at 877, 1070, 1450 and 1540 cm$^{-1}$ represent different vibrational modes of bicarbonates [14], and the peak centered at 1780 cm$^{-1}$ is the C = O vibration mode of calcite carbonate [62]. The peaks centered at 2500, 2850 and 2950 cm$^{-1}$ are assigned to the formate species, which was derived from the hydrogenation of bicarbonate assisted by the hydrogen on Ni particles in reduced catalysts as previously reported [63]. These results indicate the formation of formate, calcite carbonate and bicarbonate species after CO$_2$ capture stage during the ICCU process caused by the chemical reaction between CaO sites and the introduced CO$_2$ gas phase. The IR bands centered at 2114 and 2176 cm$^{-1}$ are attributed to the CO species due to the oxygen vacancies in CeO$_2$ will direct cleavage CO$_2$. After switching the feed gas to H$_2$, the intensities of the above-mentioned calcite carbonate and formate species remain almost unchanged. However, the peak intensity of CO species are gradually decreased, while the IR band at 3016 cm$^{-1}$ attributed to CH$_4$ species can be detected as shown in Fig. 5b, implying that CO is probably intermediate and conveted to CH$_4$ during the 2nd stage of ICCU. This is because the formed CO species react with dissociated hydrogen on Ni metallic particles to release CH$_4$ in the presence of hydrogen [64]. An in-situ DRIFTS experiment included CO adsorption and subsequent H$_2$ conversion is conducted to verify the reaction schemes and the results are displayed in Fig. 5c. It is found that after introducing CO into the cell, IR bands at 2114 and 2176 cm$^{-1}$ come out immediately. After switching the feed gas to H$_2$, a peak centered at 3016 cm$^{-1}$ assigned to the CH$_4$ species can be detected. This further confirms that CO is converted to CH$_4$ over the 1%Ni/CeO$_2$-CaO.

DFT calculations further investigated the role of nickel on the

<table>
<thead>
<tr>
<th>Samples</th>
<th>CH$_4$ yield (mmol g$^{-1}$ Ni)</th>
<th>CO$_2$ conversion(%)</th>
<th>CH$_4$ selectivity(%)</th>
<th>TOF(h$^{-1}$)</th>
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<tr>
<td>CeO$_2$-CaO</td>
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<td>0.00</td>
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<tr>
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<td>85.9</td>
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<td>63.1</td>
<td>83.6</td>
<td>20</td>
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</tbody>
</table>

* TOF = number of moles CH$_4$ product / (number of Ni active centres*reaction time)
selectivity of the overall process. Based on the HRTEM (Fig. 1), (1 1 0) lattice plane is the preferentially exposed surface of CeO₂ nanorods. Therefore, a ceria (1 1 0) supercell structure with a single oxygen vacancy (Ov-CeO₂(1 1 0)) was constructed and optimised, on top of which a sub-nanometer Ni active site was supported, as shown in Fig. 6. After optimisation, CO adsorption energies were calculated for both systems, revealing \( E_b \) of \(-0.23 \) eV and \(-1.88 \) eV on Ov-CeO₂(1 1 0) and Ni/CeO₂(1 1 0), respectively. The low CO binding strength to Ov-CeO₂(1 1 0) reflects a high potential for spontaneous desorption, as observed by in situ IR spectra that no obvious peaks assigned to the CO adsorption on CeO₂ are observed (Fig. S18). This accounts for the selectivity of CO₂ reduction over ceria nanorods (Fig. 4). With the deposition of Ni cluster, the binding strength of CO on Ni/CeO₂(1 1 0) surface is significantly enhanced, which increases the likelihood of further reaction and accounts for the shift to methane for Ni doped ceria nanorods.

From our experimental results and DFT calculation, the mechanism of CO₂ methanation over Ni/CeO₂ catalysts can be summarized as follow (Fig. 7): Firstly, CO₂ molecules are chemisorbed on the partially reduced NiO-CeO₂ interface, where most of the C = O bonds are broken together with the oxygen transferring to the ceria support to restore the oxygen balance. These oxygens move around in the ceria lattice through the abundant vacancies and provide available sites for further CO₂ chemisorption. Afterwards, different reaction pathways will be created. A fraction of carbon species are converted to CO through the reverse water gas shift reaction and then hydrogenated to CH₄; simultaneously, part of the oxygens removed upon the double bonds breaking are replaced by catalyst oxygen and released as CO or CO₂, leaving reduced sites on the catalyst again. Therefore, the main products of Ni/CeO₂ sub-nanometer catalysts are CO and CH₄.

Fig. 5. In-situ DRIFTS spectra of the species formed over 1%Ni/CeO₂-CaO: (a, b) CO₂ capture stage and H₂ conversion stage during the ICCU process, respectively, (c) CO adsorption and subsequent H₂ conversion.
4. Conclusions

We have shown the synergistic coupling of earth-abundant materials for ICCU. A physical mixture of CaO and Ni/CeO$_2$, as adsorbent and catalysts, respectively, shows excellent performance for capturing CO$_2$ from flue gas, via adsorption by CaO to form CaCO$_3$, and subsequent release under a hydrogen-rich gas stream. Upon CO$_2$ desorption, which regenerates the adsorbent for subsequent cycles, catalytic CO$_2$ reduction is facilitated over Ni doped ceria nanorods. The yield and selectivity values of CH$_4$ over our optimum system 0.5%Ni/CeO$_2$-CaO of 1540 mmol g$^{-1}$ Ni and 85.8%, respectively, coupled with high stability over 10 ICCU cycles, can be ascribed to the cooperative catalytic performance of highly dispersed Ni clusters and oxygen vacancies present on Ni doped ceria nanorods. CO$_2$ is reduced to CO over oxygen vacancies on CeO$_2$, CO desorbs and diffuses to Ni sites where hydrogenation to CH$_4$, the major product, occurs. These results are expected to have a broad implication on the design and development of efficient and cost-effective materials for ICCU.

CRediT authorship contribution statement

Hongman Sun: Conceptualization, Investigation, Visualization, Formal analysis, Writing – original draft. Yu Zhang: Conceptualization, Formal analysis, Writing – review & editing. Chunfen Wang: Conceptualization, Formal analysis, Writing – review & editing. Mark A. Isaacs: Investigation, Writing – review & editing. Ahmed I. Osman: Investigation, Writing – review & editing. Yehong Wang: Investigation, Writing – review & editing. David Rooney: Investigation, Writing – review & editing. Youhe Wang: Conceptualization, Formal analysis, Writing – review & editing. Zifeng Yan: Conceptualization, Formal analysis, Writing – review & editing. Feng Wang: Supervision, Conceptualization, Writing – review & editing. Chunfei Wu: Supervision, Conceptualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References


