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# Unravelling the K-promotion effect in highly active and stable Fe<sub>5</sub>C<sub>2</sub> nanoparticles for catalytic linear $\alpha$ -olefin production†

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C<sub>5</sub>–C<sub>13</sub> linear alpha( $\alpha$ ) olefins (LAOs) are high-value-added chemicals acknowledged by industry. However, using catalysts to elevate the activity and selectivity of LAOs remains a major challenge for Fischer–Tropsch synthesis (FTS). Recently, researchers on catalyst design have reported enhanced LAO production via FTS, but a more detailed understanding of the electron interactions between the active particles and hydrocarbon products is still needed. In the present paper, we report theoretical and experimental results of a potassium (K)-promotion effect on an optimized iron-carbide nanocatalyst (*i.e.* a carbon-encapsulated iron-carbide nanoparticle supported on nitrogen-doped porous carbon: Fe<sub>5</sub>C<sub>2</sub>@C/NPC). The K-doped Fe<sub>5</sub>C<sub>2</sub>@C/NPC nanocatalyst shows excellent catalytic performance with a high CO conversion of up to 96.7% at 78 h time-on-stream, C<sub>5</sub>–C<sub>13</sub> LAO selectivity of 16.5% and productivity of 5.9 CH<sub>2</sub>  $\mu\text{mol g}_{\text{cat}}^{-1} \text{s}^{-1}$ , compared to those of the K-free Fe<sub>5</sub>C<sub>2</sub>@C/NPC catalyst. The computer simulation model also supports the positive effects of the catalyst with a small amount of K (*ca.* 1 wt%, K/Fe = 0.05) in the FTS reaction, which well-matched the experimental results.

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## Introduction

The linear alpha olefins (LAOs), linear hydrocarbons with a C=C bond at the terminal position, are chemical intermediates that are attractive for use in detergents, specialty chemicals, synthetic oils, premium synthetic lubricants and plasticizers, as well as in copolymers.<sup>1–4</sup> To date, ethylene oligomerization for homogeneous transition-metal catalysis has been a significant process for LAO production.<sup>5,6</sup> For example, more than 1 Mt of alpha olefins per year are produced using the Shell Higher Olefin Process (SHOP), which was discovered in 1968.<sup>7,8</sup> On the other hand, promising LAO production methods based on carbon monoxide (CO) and carbon dioxide (CO<sub>2</sub>) hydrogenation reactions are rarely reported due to the delicate processing

conditions and complicated catalyst properties. These are made worse by insufficient understanding of their performance.<sup>9–12</sup>

Using the high-temperature Fischer–Tropsch synthesis (HT-FTS) process, which is normally conducted at temperatures of 300–350 °C using an iron-based catalyst, hydrocarbons with carbon chains in the gasoline (C<sub>5</sub>–C<sub>12</sub>) range and C<sub>2</sub>–C<sub>4</sub> olefins have been obtained selectively.<sup>13–18</sup> However, exquisite control of the catalysts and processes is needed to achieve the desired LAO products and this remains a major challenge.

To increase olefin production, potassium (a representative alkali metal) has been widely used as an additive in HT-FTS.<sup>19–23</sup> It can donate electrons to active iron surfaces and increase catalyst basicity, leading to the enhanced performance of the catalyst. For instance, Guo *et al.* reported bio-promoted iron-carbide catalysts with K, as an efficient catalyst for converting CO<sub>2</sub> to LAOs. This combination suppressed the secondary hydrogenation of alkenes on active surfaces.<sup>24</sup> Recently, the Tsubaki group reported a bimetallic FeCo catalyst with Y-zeolite for the selective production of LAOs by CO<sub>2</sub> hydrogenation.<sup>25</sup> Although some iron-based catalysts with alkali promoters have been reported for LAO production, research using computational simulation to interpret their roles in catalysis is still insufficient.<sup>26–29</sup>

For more efficient production of high value-added hydrocarbons in HT-FTS, active and thermally stable nanocatalysts such as Fe@C core-shells and Fe@graphene with a high Fe

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load (> 20 wt%) and small particle sizes (< 20 nm) have been developed.<sup>30–33</sup> The catalysts, which have active Fe sites greatly exposed in the FTS reaction, have demonstrated increased productivity of valuable hydrocarbons.

In our previously published work, we reported a new active and stable Fe<sub>5</sub>C<sub>2</sub>@C catalyst supported on a structure of N-doped carbon as an optimum catalyst for HT-FTS.<sup>34</sup> In addition, we have found that the appropriate K-doping ratios (K/Fe atomic ratio) at the K-doped  $\chi$ -Fe<sub>5</sub>C<sub>2</sub>/charcoal catalysts are in the range of 0.050–0.075.<sup>29</sup> From the investigation of the K-promotion effect on the catalyst based on computer simulation, we prepared K-promoted, carbon-encapsulated iron-carbide nanoparticles supported on a nitrogen-doped porous carbon nanostructure (K-Fe<sub>5</sub>C<sub>2</sub>@C/NPC). It showed a higher CO conversion rate and better selectivity for linear alpha olefins (LAOs) than those of the K-free Fe<sub>5</sub>C<sub>2</sub>@C/NPC catalyst. Furthermore, the initial induction period during the FTS reaction using the catalyst with small amounts of K was significantly reduced, resulting in an increase of overall liquid hydrocarbon productivity, including that of LAOs. The catalyst showed a high C<sub>5</sub>–C<sub>13</sub> LAO productivity of 5.9 CH<sub>2</sub>  $\mu\text{mol g}_{\text{cat}}^{-1} \text{s}^{-1}$ , which is  $\sim 1.5$  times higher than that of the K-free Fe<sub>5</sub>C<sub>2</sub>@C/NPC catalyst (4.0 CH<sub>2</sub>  $\mu\text{mol g}_{\text{cat}}^{-1} \text{s}^{-1}$ ) as well as good thermal stability for the HT-FTS reaction carried out at 340 °C and 1.5 MPa for 78 h.

## Experimental

### Chemicals

Iron(III) acetylacetonate (Fe(C<sub>5</sub>H<sub>7</sub>O<sub>2</sub>)<sub>3</sub>, Aldrich,  $\geq 99.9\%$ ), urea (CH<sub>4</sub>N<sub>2</sub>O) (Aldrich, 99.0–100.5%), potassium carbonate (K<sub>2</sub>CO<sub>3</sub>, Aldrich,  $\geq 98.0\%$ ) and ethanol (C<sub>2</sub>H<sub>5</sub>OH, J.T. Baker, 99.9%) were used without further purification.

### Computational details

The plane-wave-based spin-polarized density functional theory (DFT) calculations implemented in the Vienna *Ab initio* Simulation Package (VASP)<sup>35–38</sup> were performed to investigate the K-promotion effect on the atomic/electronic structures and adsorption properties of Fe<sub>5</sub>C<sub>2</sub> nanoparticles. The vdW-DF2 functional proposed by Langreth and Lundqvist *et al.* was used to describe the exchange correlation energy as implemented in the VASP by Klimeš *et al.*<sup>39–42</sup> The projector augmented wave (PAW)<sup>43, 44</sup> method was used to describe the interactions between the core and valence electrons. The Kohn–Sham single-electron wave function was expanded by plane-wave basis sets with a cut-off energy of 500 eV. The convergence criteria for the electronic energy and geometry optimization were set at 10<sup>–5</sup> eV and 0.02 eV Å<sup>–1</sup>, respectively. The Brillouin zone was sampled at the *I*-point in all the DFT calculations. First-principles molecular dynamics simulations were employed to generate a reliable nanoparticle model structure. A Fe<sub>5</sub>C<sub>2</sub> nanoparticle structure was prepared by cutting a single crystalline Hägg iron carbide (Fe<sub>5</sub>C<sub>2</sub>) structure while maintaining the stoichiometry. Then, the structure was annealed by ramping the temperature from 0 to 1800 K for 100 fs followed by equilibration at 1800 K for 1 ps. The final structure was obtained

by ensemble average from the last 500 snapshots during equilibration. The Fe<sub>5</sub>C<sub>2</sub> nanoparticle structure was then quenched to 0 K for 100 ps and relaxed by geometry optimization until the maximal force acting on each atom became less than 0.02 eV Å<sup>–1</sup>. For a K-doped Fe<sub>5</sub>C<sub>2</sub> nanoparticle structure, the location of two K atoms was chosen as the energetically most-stable configuration among the eight cases considered (see Fig. S1, ESI†).

### Synthesis of the K-Fe<sub>5</sub>C<sub>2</sub>@C/NPC nanocatalyst

The synthesis of the K-free Fe<sub>5</sub>C<sub>2</sub>@C/NPC nanocatalyst was described in detail in our previous publication.<sup>34</sup> Briefly, 0.5 g of Fe(C<sub>5</sub>H<sub>7</sub>O<sub>2</sub>)<sub>3</sub> (1.4 mmol) and 2.5 g of CH<sub>4</sub>N<sub>2</sub>O (41.6 mmol) were mixed to uniformity by grinding in a mortar for 5 min. The powder mixture was transferred to alumina boats in a tube-type furnace. The mixture was then heated to 700 °C at a ramping rate of 5.6 °C min<sup>–1</sup> under a N<sub>2</sub> flow (200 mL min<sup>–1</sup>) and then maintained at the same temperature for 2 h. After this, serial thermal treatments were carried out under a H<sub>2</sub> flow (200 mL min<sup>–1</sup>) for 4 h at 350 °C, followed by a CO flow (200 mL min<sup>–1</sup>) for 4 h at 350 °C. Finally, the resulting black powder was cooled to room temperature and then submerged in 30 mL of ethanol under a flow of N<sub>2</sub> (500 mL min<sup>–1</sup>). The powder immersed in 30 mL of ethanol was simply separated using a magnet and then dried in a vacuum oven. For the preparation of the K-doped Fe<sub>5</sub>C<sub>2</sub>@C/NPC nanocatalyst, the incipient wetness method was used to merge a K additive with the dried Fe<sub>5</sub>C<sub>2</sub>@C/NPC nanocatalyst powder. A solution of aqueous K<sub>2</sub>CO<sub>3</sub> in distilled water (1 mL, 0.024 M) was used. After impregnation with the K solution, the K-incorporated sample was transferred to an alumina boat in a tube-type furnace and then slowly heated at a ramping rate of 2.7 °C min<sup>–1</sup> to 350 °C under a CO flow (200 mL min<sup>–1</sup>). The sample was allowed to remain at 350 K for 4 h under a continuous CO flow. After the thermal treatment, the resulting black powder was cooled to room temperature and then submerged in ethanol under a N<sub>2</sub> flow to prevent rapid surface oxidation. The K-Fe<sub>5</sub>C<sub>2</sub>@C/NPC nanocatalyst powders were simply separated by magnetic force and then completely dried in a vacuum oven at 50 °C.

### High-temperature Fischer–Tropsch synthesis reaction

The reaction tests were performed in a fixed-bed stainless-steel reactor tube with an inner diameter of 5 mm. Some (0.1 g) of the catalyst sample were diluted with glass beads (425–600  $\mu\text{m}$ , 2.9 g) to prevent hot-spot generation during the severe exothermic reaction. Before the reaction, the catalyst was reduced *in situ* under atmospheric pressure by passing a flow of CO (40 mL min<sup>–1</sup>) over it at 350 °C for 4 h. After reduction, the reaction tests were carried out at 340 °C and 1.5 MPa for 78 h using reactant gas (H<sub>2</sub>/CO = 1.0 and gas hourly space velocity (GHSV) = 42 NL g<sub>cat</sub><sup>–1</sup> h<sup>–1</sup>). The composition of the outlet gases was analysed using a gas chromatograph (Agilent, 3000 Micro GC) equipped with a thermal conductivity detector (TCD) and flame ionization detector (FID). The flow rates of the outlet gases were measured using a wet-gas flow meter (Shinagawa Co.). After the reaction, the solid hydrocarbon products were collected in a hot trap (240 °C) and the liquid hydrocarbon products and water were collected in a cold trap



(−3 °C). The isolated solid (wax) and liquid (oil) products were analysed using an offline gas chromatograph (Agilent, 6890 N) and the simulated distillation method (ASTM D2887). Detailed hydrocarbon analysis (DHA) of C<sub>5</sub>–C<sub>13</sub> LAOs (wt%) in the liquid oil sample was performed using ultra-high-resolution capillary gas chromatography and ASTM D6730.

### Characterization

Transmission electron microscopy (TEM) images and high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) images were obtained using a Talos F200X operated at 200 kV. Energy-dispersive X-ray spectroscopy (EDS) elemental analysis and a mapping process were performed using a higher efficiency detection system (Super X: 4 windowless SDD EDS system). The X-ray diffraction (XRD) patterns of the samples were recorded on a high-power powder X-ray diffractometer (Rigaku D/MAX-2500, 18 kW). The N<sub>2</sub> sorption isotherms were measured at 77 K with a TriStar II 3020 surface area analyser. Before the measurement, the samples were degassed in a vacuum at 573 K for 4 h. X-ray photoelectron spectroscopy (XPS) was carried out using a K-alpha (TM) with a micro-focused monochromator X-ray source (Thermo VG Scientific, Inc.). The Fe loading amount was measured using inductively coupled plasma optical emission spectrometry (ICP-OES, Thermo Scientific iCAP 6300) and the content of K was determined using ICP-OES (Agilent 5110). The N content in the sample was measured using an oxygen–nitrogen–hydrogen analyser (ONH-2000, ELTRA GmbH). Raman analysis was performed using a Raman microscope (Horiba LabRAM HR Evolution Visible\_NIR) with a 514 nm laser.

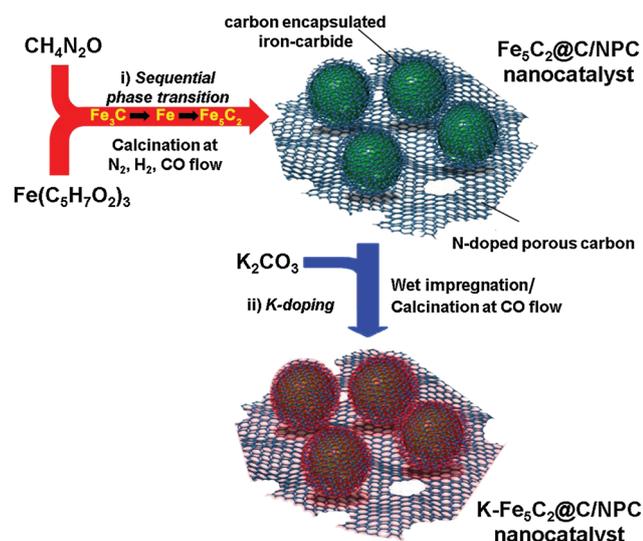
## Results and discussion

### Synthesis of the K-doped Fe<sub>5</sub>C<sub>2</sub>@C/NPC nanocatalyst

The K-Fe<sub>5</sub>C<sub>2</sub>@C/NPC nanocatalyst was prepared through a sequential thermal treatment and the incipient wetness method (Scheme 1). First, the mixed compound prepared by

physically grinding Fe(C<sub>5</sub>H<sub>7</sub>O<sub>2</sub>)<sub>3</sub> (iron precursor) and CH<sub>4</sub>N<sub>2</sub>O (nitrogen-doped carbon source) was transformed by thermal treatment under N<sub>2</sub> gas at 700 °C, H<sub>2</sub> gas at 350 °C and a CO atmosphere at 350 °C to achieve the desired phases (Fe<sub>3</sub>C by the initial N<sub>2</sub> treatment, Fe by the sequential H<sub>2</sub> treatment, and Fe<sub>5</sub>C<sub>2</sub> by the sequential CO treatment). After the serial thermal treatment, a K-free Fe<sub>5</sub>C<sub>2</sub>@C/NPC nanocatalyst was obtained. Next, to obtain the K-Fe<sub>5</sub>C<sub>2</sub>@C/NPC nanocatalyst, aqueous K solution using the K<sub>2</sub>CO<sub>3</sub> salt as a K source was used to impregnate the Fe<sub>5</sub>C<sub>2</sub>@C/NPC nanocatalyst powders. This was followed by the performance of additional CO treatment at 350 °C. In the catalyst, the K-doped Fe<sub>5</sub>C<sub>2</sub> nanoparticles were well dispersed on the carbon structure.

The transmission electron microscopy (TEM) images show the overall structures for the K-free and K-doped Fe<sub>5</sub>C<sub>2</sub>@C/NPC nanocatalyst (Fig. 1a and b, respectively). The average particle size was 17.2 nm for K-free Fe<sub>5</sub>C<sub>2</sub>@C/NPC and 17.4 nm for K-Fe<sub>5</sub>C<sub>2</sub>@C/NPC, as determined by measuring 200 particles in the



Scheme 1 Brief synthetic scheme of the K-Fe<sub>5</sub>C<sub>2</sub>@C/NPC nanocatalyst.

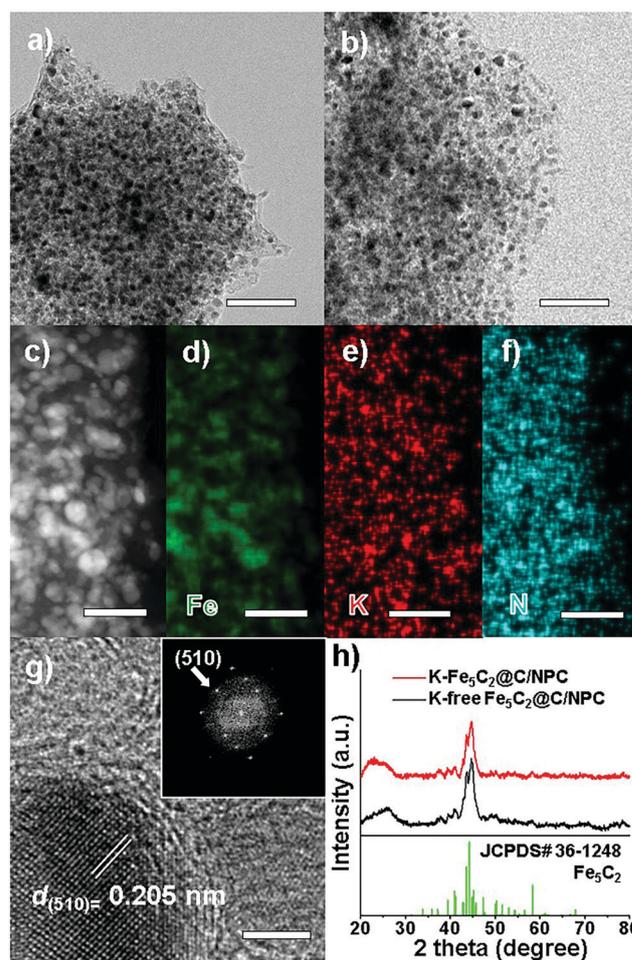


Fig. 1 TEM images of (a) K-free Fe<sub>5</sub>C<sub>2</sub>@C/NPC and (b) K-Fe<sub>5</sub>C<sub>2</sub>@C/NPC, (c) HAADF-STEM image and (d–f) elemental mapping images (green: Fe, red: K, cyan: N), and (g) HR-TEM image with the corresponding Fourier-transform pattern (inset of g) of the K-Fe<sub>5</sub>C<sub>2</sub>@C/NPC nanocatalyst. (h) XRD spectra of the K-free and K-doped Fe<sub>5</sub>C<sub>2</sub>@C/NPC nanocatalysts. The bars represent 100 nm (a and b), 50 nm (c–f) and 3 nm (g), respectively.



TEM images (Fig. S2, ESI<sup>†</sup>). The high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) image clearly shows Fe<sub>5</sub>C<sub>2</sub> nanoparticles as relatively bright spots originating from the Fe atoms (Fig. 1c). The elemental mappings of iron (green), potassium (red) and nitrogen (cyan) also indicate the uniform distribution of each component (Fig. 1d–f). The HRTEM image shows spherical K-Fe<sub>5</sub>C<sub>2</sub> nanoparticles encapsulated within carbon shells (Fig. 1g). The carbon shells which encapsulate the nanoparticles originated from the carbonized product of urea during the initial calcination process under nitrogen gas. The lattice distance between neighbouring fringes (0.205 nm) and the corresponding Fourier-transform (FT) patterns, demonstrated the formation of iron-carbide crystals that matched the (510) planes of Hägg iron-carbide (Fe<sub>5</sub>C<sub>2</sub>).

The X-ray diffraction (XRD) spectra of the K-free and K-doped Fe<sub>5</sub>C<sub>2</sub>@C/NPC nanocatalysts show that both kinds of iron carbide particles well-matched with the Fe<sub>5</sub>C<sub>2</sub> phase (Fig. 1f, JCPDS No. 36-1248; space group, C2/c). The broad diffraction peak near  $2\theta = 25^\circ$  corresponds to the (002) plane of amorphous carbon. There was no difference between K-Fe<sub>5</sub>C<sub>2</sub>@C/NPC and K-free Fe<sub>5</sub>C<sub>2</sub>@C/NPC nanocatalysts. Using the Debye–Scherrer equation on the basis of peak broadening of the (020) reflection, the average crystal size of the Fe<sub>5</sub>C<sub>2</sub> nanoparticles was calculated to be 17.2 nm for K-free Fe<sub>5</sub>C<sub>2</sub>@C/NPC and 17.5 nm for the K-doped Fe<sub>5</sub>C<sub>2</sub>@C/NPC nanocatalyst. These results suggest that the K-doping in the catalyst caused no significant change in either the size or phase of the crystals.

To investigate the chemical structure and elemental surface state of Fe and N in the K-free and K-doped Fe<sub>5</sub>C<sub>2</sub>@C/NPC nanocatalysts, X-ray photoelectron spectroscopy (XPS) analysis was performed. The XPS spectra of the energy region of the Fe band exhibited assigned peaks from iron carbide (Fe(0)) at 706–707 eV and from iron-oxides (Fe(2+) and Fe(3+)) at 710–711 eV (Fig. 2a). Partial oxidation of the active iron-carbide nanoparticles occurs due to exposure to the atmosphere during the sampling processes. In the XPS spectrum, the K-doped Fe<sub>5</sub>C<sub>2</sub> nanoparticles showed less intense peaks in the binding-energy ranges. Potassium can effectively stabilize the reduced iron surface against oxidation, as reported elsewhere.<sup>45</sup> Because neighbouring K was more easily oxidized than Fe<sub>5</sub>C<sub>2</sub>, iron oxidation was suppressed. At the core-level the XPS spectrum of N 1s, two split peaks corresponding to pyridinic N at 400.6 eV and pyrrolic N at 398.4 eV were observed in both K-free and K-doped Fe<sub>5</sub>C<sub>2</sub>@C/NPC nanocatalysts (Fig. 2b).

To evaluate the crystallinity and structure of the porous carbon framework of the K-Fe<sub>5</sub>C<sub>2</sub>@C/NPC nanocatalyst, Raman spectroscopy was performed (Fig. 2c). The G band near 1580 cm<sup>-1</sup> is characteristic of the vibration of sp<sup>2</sup>-bonded carbon atoms in a 2D hexagonal lattice (E<sub>2g</sub> mode). The strong peak at around 1350 cm<sup>-1</sup>, called the D band, was ascribed to the dangling bonds of the in-plane terminations of disordered graphite. The second-order 2D band in the range of 2500–3000 cm<sup>-1</sup> is typical of graphitic sp<sup>2</sup> materials. The N-doped porous carbon demonstrated a high I<sub>D</sub>/I<sub>G</sub> value (~1.0), suggesting the presence of many disordered sites in the carbon matrix.

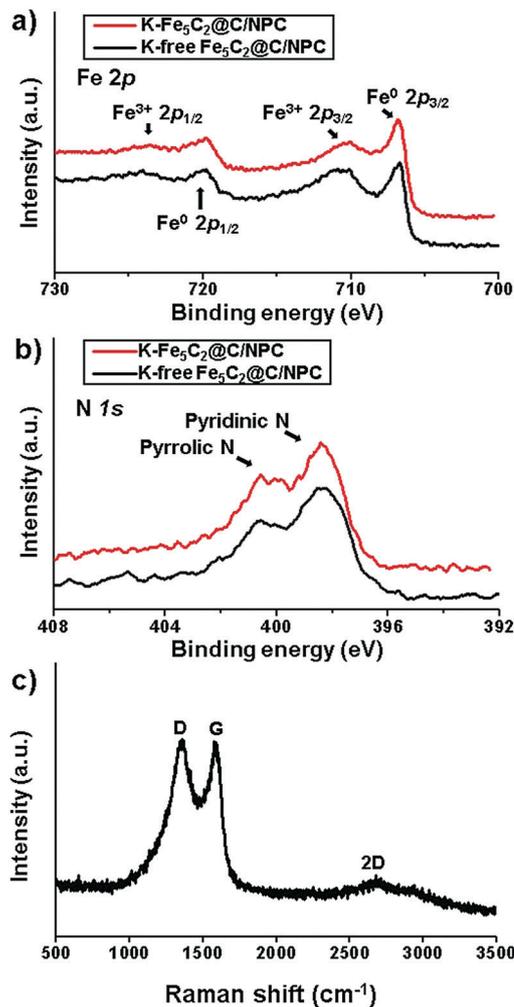


Fig. 2 XPS spectra in the energy regions of (a) Fe 2p and (b) N 1s of the K-free Fe<sub>5</sub>C<sub>2</sub>@C/NPC and K-Fe<sub>5</sub>C<sub>2</sub>@C/NPC nanocatalysts and (c) Raman spectrum of the K-Fe<sub>5</sub>C<sub>2</sub>@C/NPC nanocatalyst.

The Brunauer–Emmett–Teller (BET) surface area and the porosity in the samples were investigated by N<sub>2</sub> sorption measurements (Fig. 3a). The K-Fe<sub>5</sub>C<sub>2</sub>@C/NPC nanocatalyst exhibited type IV adsorption–desorption hysteresis. The BET surface area and the pore volume measured were found to be 284.0 m<sup>2</sup> g<sup>-1</sup> and 0.22 cm<sup>3</sup> g<sup>-1</sup>, respectively. The pore size, calculated by the Barrett–Joyner–Halenda (BJH) method on the desorption branch, was observed to be 3.7 nm (Fig. 3b). From the results of inductively coupled plasma optical emission spectroscopy (ICP-OES), the Fe and K contents were found to be 33.7 and 1.3 wt%, respectively. The total N content in the Fe<sub>5</sub>C<sub>2</sub>@C/NPC sample was determined to be 5.0% using a nitrogen analyser (OHN-2000).

### High-temperature Fischer–Tropsch synthesis (HT-FTS)

The reaction test with the K-Fe<sub>5</sub>C<sub>2</sub>@C/NPC nanocatalyst was performed at 1.5 MPa, 340 °C and a H<sub>2</sub>/CO ratio = 1, under the high gas hourly space velocity (GHSV) conditions of 42 NL g<sub>cat</sub><sup>-1</sup> h<sup>-1</sup>. The CO conversion and selectivity of the catalysts were measured



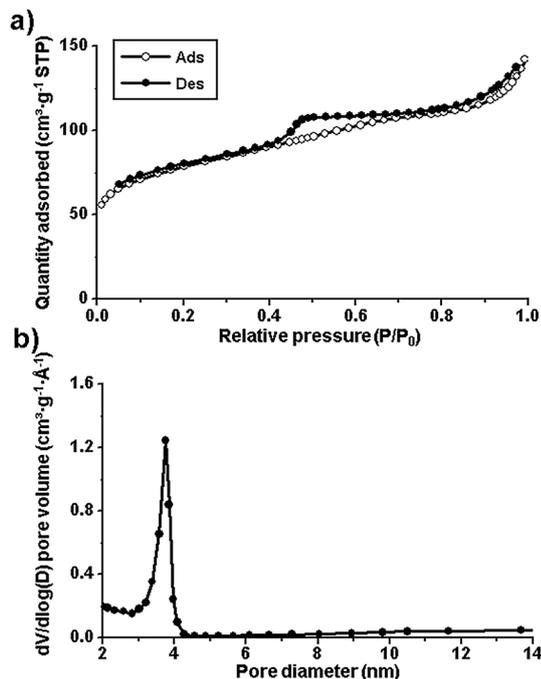
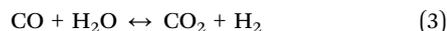
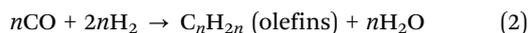
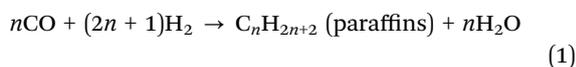


Fig. 3 (a)  $N_2$  sorption isotherms and (b) pore size distribution diagram of the K- $Fe_5C_2@C/NPC$  nanocatalyst.

for 72 h over time-on-stream (TOS) by gas chromatography (GC) of the outlet gases containing the unreacted CO,  $H_2$ ,  $CH_4$ ,  $C_2-C_4$  hydrocarbons and  $CO_2$ . Liquid oil and solid wax recovered in a cold trap and a hot trap, respectively, were further analysed using simulated distillation (SIMDIS). The K-free  $Fe_5C_2@C/NPC$  nanocatalyst was also used under the same reaction conditions for comparison with the K-doped  $Fe_5C_2@C/NPC$  nanocatalyst.

In HT-FTS, the reactions for paraffin and olefin hydrocarbon-product formation and the water-gas shift (WGS) reaction occur as indicated below:



The K- $Fe_5C_2@C/NPC$  nanocatalyst exhibited very high CO conversion even under high GHSV conditions of  $42 \text{ NL g}_{\text{cat}}^{-1} \text{ h}^{-1}$  (Fig. 4a). The CO conversion in the K-free  $Fe_5C_2@C/NPC$  catalyst gradually increased until  $\sim 78$  h from 63.5% at TOS = 12 h to 96.0% at TOS = 78 h. On the other hand, the K- $Fe_5C_2@C/NPC$  nanocatalyst showed much more rapidly stabilized CO conversions of 72.3% at TOS = 12 h and 92.5% at TOS = 18 h, finally reaching 96.7% at TOS = 78 h (Fig. 4b). The selectivity data of the K-doped  $Fe_5C_2@C/NPC$  nanocatalyst at TOS = 78 h were calculated to be  $CO_2$  (39.4%),  $CH_4$  (9.6%),  $C_2-C_4$  (15.2%) and  $C_{5+}$  (35.8%) (Fig. 4c). These values are comparable to those of the K-free  $Fe_5C_2@C/NPC$  nanocatalyst ( $CO_2$ : 41.2%,  $CH_4$ : 10.2%,  $C_2-C_4$ : 15.1%,  $C_{5+}$ : 33.5%) (Fig. 4d).

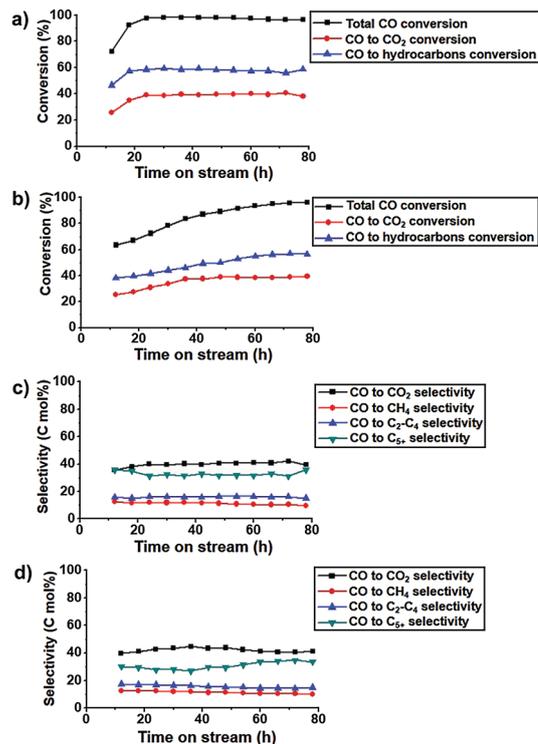


Fig. 4 (a and b) CO conversion and (c and d) Hydrocarbon product selectivity graph (a and c: K- $Fe_5C_2@C/NPC$  nanocatalysts; b and d: K-free  $Fe_5C_2@C/NPC$  nanocatalysts). The reaction tests were conducted at  $340^\circ\text{C}$ , 1.5 MPa, GHSV =  $42 \text{ NL g}_{\text{cat}}^{-1} \text{ h}^{-1}$  and a  $H_2 : CO$  ratio of 1. The total CO conversion is the sum of the CO conversion to hydrocarbons (CO to HC) and the CO conversion to  $CO_2$  (CO to  $CO_2$ ).

The activities of the catalysts were monitored as the iron-time-yield (FTY, *i.e.* the number of CO moles converted to hydrocarbons per gram of iron per second) over TOS (Fig. 5a). The K- $Fe_5C_2@C/NPC$  nanocatalyst showed much faster stabilization behaviour, with a rapid increase of the FTY values (up to  $4.4 \times 10^{-4} \text{ mol}_{\text{CO}} \text{ g}_{\text{Fe}}^{-1} \text{ s}^{-1}$ ), than did the K-free  $Fe_5C_2@C/NPC$  nanocatalyst. The FTY value of the K- $Fe_5C_2@C/NPC$  nanocatalyst was very high relative to the results reported previously for K-doped Fe catalysts (Table S1, ESI<sup>†</sup>). From the results, it was confirmed that the K added to the  $Fe_5C_2$  particles contributes to the activation of the catalyst and increases the reactivity.

To determine the hydrocarbon product distributions and specific hydrocarbon productivity, the detailed composition of the liquid and solid hydrocarbons was determined by ASTM D2887 (Fig. 5b). The K- $Fe_5C_2@C/NPC$  nanocatalyst showed higher  $C_2-C_4$  olefins (16.7%) and diesel range  $C_{13}-C_{18}$  hydrocarbons (4.4%), compared to K-free  $Fe_5C_2@C/NPC$  (Fig. 5c). The trend toward heavier hydrocarbons with this catalyst was also observed in relation to the chain-growth probability ( $\alpha$  value) of the hydrocarbons. This was determined using the Anderson-Schulz-Flory (ASF) chain-growth mechanism in the following equation, where  $W_n$  is the weight fraction of hydrocarbons with carbon number  $n$  (Fig. 5d):

$$\log(W_n/n) = \log(\ln^2 \alpha) + n \log \alpha$$



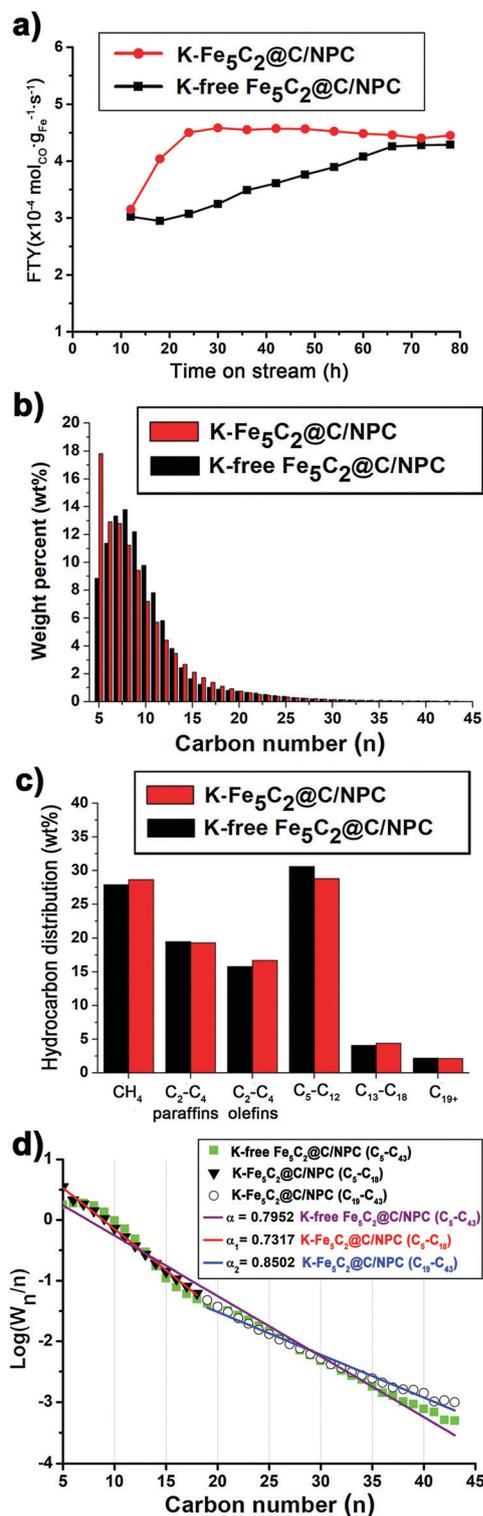


Fig. 5 (a) FT activity, (b) total syn crude ( $C_5+$  hydrocarbons) distribution graphs, (c) Total hydrocarbon product distribution, and (d) ASF plots of  $C_5+$  hydrocarbons and chain-growth probability.

The  $\alpha$  value of the hydrocarbons by K-free  $Fe_5C_2@C/NPC$  was calculated to be 0.7952, using the slope of the graph fitted to the linear regression at  $C_5-C_{43}$ . On the other hand, K-free

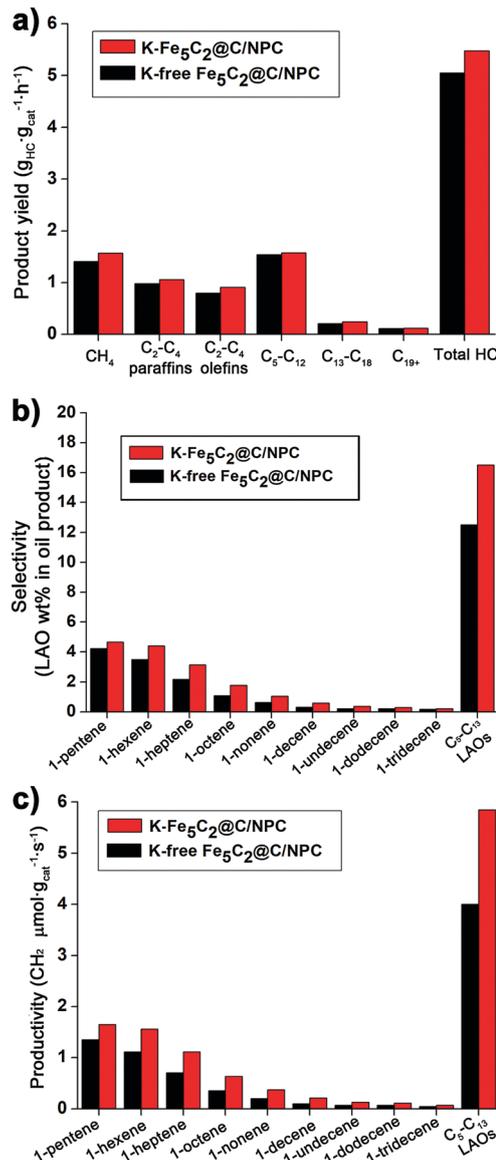


Fig. 6 (a) Specific hydrocarbon productivity and (b)  $C_5-C_{13}$  LAO selectivity and (c) productivity of K-free  $Fe_5C_2@C/NPC$  and K- $Fe_5C_2@C/NPC$  nanocatalysts.

$Fe_5C_2@C/NPC$  showed two  $\alpha$  values ( $\alpha_1 = 0.7317$  at  $C_5-C_{18}$  and  $\alpha_2 = 0.8502$  at  $C_{19}-C_{43}$ ) which are attributed to the K-lean sites and K-rich sites of the catalyst, respectively.

The total hydrocarbon (HC) product yield (grams of hydrocarbons generated per gram of iron per second) was measured after 78 h on-stream of the reaction (Fig. 6a). The K- $Fe_5C_2@C/NPC$  nanocatalyst shows a higher hydrocarbon product yield ( $5.48 \text{ g}_{\text{HC}} \text{ g}_{\text{cat}}^{-1} \text{ h}^{-1}$ ), than that of the K-free  $Fe_5C_2@C/NPC$  nanocatalyst ( $5.05 \text{ g}_{\text{HC}} \text{ g}_{\text{cat}}^{-1} \text{ h}^{-1}$ ). The yields using the former were calculated using the sum of the specific product yields [ $CH_4$  (1.57),  $C_2-C_4$  paraffins (1.06),  $C_2-C_4$  olefins (0.91),  $C_5-C_{12}$  (1.58),  $C_{13}-C_{18}$  (0.24) and  $C_{19+}$  (0.12)  $\text{g}_{\text{HC}} \text{ g}_{\text{cat}}^{-1} \text{ h}^{-1}$ ]. The detailed yield values of each hydrocarbon product for the K-free  $Fe_5C_2@C/NPC$  nanocatalyst were  $CH_4$  (1.41),  $C_2-C_4$



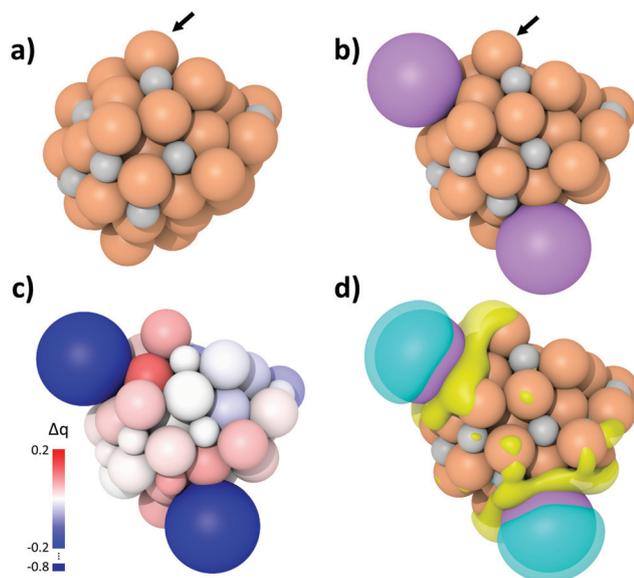


Fig. 7 Geometry optimized structure of (a) K-free  $\text{Fe}_5\text{C}_2$  and (b) K doped  $\text{Fe}_5\text{C}_2$  nanoparticles. Dark orange, grey and purple balls indicate Fe, C and K atoms, respectively. (c) Bader charge difference and (d) differential charge density between K-free and K- $\text{Fe}_5\text{C}_2$  nanoparticles. The isosurface level was set to  $0.003 \text{ e bohr}^{-3}$ . Yellow and cyan colors in the isosurface represent charge accumulation and depletion, respectively.

paraffins (0.98),  $\text{C}_2$ – $\text{C}_4$  olefins (0.80),  $\text{C}_5$ – $\text{C}_{12}$  (1.54),  $\text{C}_{13}$ – $\text{C}_{18}$  (0.21), and  $\text{C}_{19+}$  (0.11)  $\text{g}_{\text{HC}} \text{g}_{\text{cat}}^{-1} \text{h}^{-1}$ .

The specific  $\text{C}_5$ – $\text{C}_{13}$  LAO content in the liquid oil sample recovered after the HT-FTS reactions was obtained by detailed hydrocarbon analysis. The K- $\text{Fe}_5\text{C}_2$ @C/NPC nanocatalyst also showed higher selectivity for  $\text{C}_5$ – $\text{C}_{13}$  LAOs (16.5 wt%), which is the sum of  $\text{C}_5$  LAO (4.7 wt%),  $\text{C}_6$  LAO (4.4 wt%),  $\text{C}_7$  (3.2 wt%),  $\text{C}_8$  LAO (1.8 wt%),  $\text{C}_9$  LAO (1.1 wt%),  $\text{C}_{10}$  LAO (0.6 wt%),  $\text{C}_{11}$  LAO (0.4 wt%),  $\text{C}_{12}$  LAO (0.3 wt%), and  $\text{C}_{13}$  LAO (0.2 wt%), compared to the K-free  $\text{Fe}_5\text{C}_2$ @C/NPC nanocatalyst (12.5 wt%) (Fig. 6b). The  $\text{C}_5$ – $\text{C}_{13}$  LAO productivity data (the number of  $\text{CH}_2$  micromoles assigned to LAOs per gram of catalyst per second) of reactions with K-free  $\text{Fe}_5\text{C}_2$ @C/NPC and K- $\text{Fe}_5\text{C}_2$ @C/NPC nanocatalysts were also calculated, based on the  $\text{C}_5$ – $\text{C}_{13}$  LAO contents obtained (Fig. 6c). The K- $\text{Fe}_5\text{C}_2$ @C/NPC nanocatalyst showed  $\sim 1.5$  times higher total  $\text{C}_5$ – $\text{C}_{13}$  LAO productivity ( $5.9 \text{ CH}_2 \mu\text{mol g}_{\text{cat}}^{-1} \text{s}^{-1}$ ) than that of the K-free  $\text{Fe}_5\text{C}_2$ @C/NPC nanocatalyst ( $4.0 \text{ CH}_2 \mu\text{mol g}_{\text{cat}}^{-1} \text{s}^{-1}$ ).

After 78 h of the HT-FTS reaction, the recovered K- $\text{Fe}_5\text{C}_2$ @C/NPC nanocatalyst showed high stability, maintaining its original structure without particle aggregation, as a result of the carbon shells protecting the  $\text{Fe}_5\text{C}_2$  particles (Fig. S3, ESI<sup>†</sup>).

### Theoretical investigation of the K-promotion effect

To elucidate the origin of the enhanced LAO selectivity, spin-polarized DFT calculations and subsequent charge density analyses were performed for the K-free  $\text{Fe}_5\text{C}_2$  and K- $\text{Fe}_5\text{C}_2$  nanoparticles (Fig. 7a and b). Both Bader charge and differential charge density analyses revealed that K adsorption on the  $\text{Fe}_5\text{C}_2$  nanoparticles promotes active electron transfer from K to the

Table 1 Calculated adsorption energy of  $\text{C}_5$ – $\text{C}_8$  olefins on the K-free  $\text{Fe}_5\text{C}_2$  and K- $\text{Fe}_5\text{C}_2$  nanoparticles

System	Adsorption energy (eV)			
	$\text{C}_5\text{H}_{10}$	$\text{C}_6\text{H}_{12}$	$\text{C}_7\text{H}_{14}$	$\text{C}_8\text{H}_{16}$
K-free $\text{Fe}_5\text{C}_2$	−1.30	−1.59	−1.35	−1.72
K- $\text{Fe}_5\text{C}_2$	−0.81	−1.01	−0.55	−1.15

adjacent Fe atoms and that these Fe atoms become less positively charged (Fig. 7c and d). The active electron transfer and charge state of the substrate metal atoms have been demonstrated to play an important role in determining the adsorption strength between olefins and metal atoms *via*  $\pi$ -complexation. In such cases, the metal atoms with more positive charges enhance olefin adsorption.<sup>46–50</sup> Thus, the olefin adsorption calculations on the K-free  $\text{Fe}_5\text{C}_2$  and K- $\text{Fe}_5\text{C}_2$  nanoparticles were performed (Fig. S4, ESI<sup>†</sup>) and the adsorption energy was calculated using the following equation:

$$E_{\text{ads}} = E_{(\text{olefin/nanoparticle})} - [E_{(\text{olefin})} + E_{(\text{nanoparticle})}]$$

where  $E_{(\text{olefin})}$ ,  $E_{(\text{nanoparticle})}$  and  $E_{(\text{olefin/nanoparticle})}$  are the total energy of an isolated olefin molecule, the K-free nanoparticle or K- $\text{Fe}_5\text{C}_2$  nanoparticle and the system after adsorption, respectively. The adsorption site was chosen to be the Fe atom adjacent to K indicated by an arrow in Fig. 7a and b. The calculated adsorption energies of  $\text{C}_5$ – $\text{C}_8$  olefins on the K-free  $\text{Fe}_5\text{C}_2$  and K- $\text{Fe}_5\text{C}_2$  nanoparticles are summarized (Table 1). It was clearly observed that the adsorption energy of olefins on the K- $\text{Fe}_5\text{C}_2$  nanoparticles becomes weaker than that on K-free  $\text{Fe}_5\text{C}_2$  nanoparticles, which is attributed to electron accumulation on the Fe atoms. Therefore, we postulate that K doping of  $\text{Fe}_5\text{C}_2$  nanoparticles promotes facile dissociation of  $\text{C}_5$ – $\text{C}_8$  olefins *via* lowering of the chemisorption energy.

## Conclusions

K-doped  $\text{Fe}_5\text{C}_2$ @C/NPC nanocatalyst, bearing highly active and stable  $\text{Fe}_5\text{C}_2$  nanoparticles ( $\sim 17 \text{ nm}$ ) encapsulated within carbon shells, were prepared *via* subsequent thermal treatment under the flows of  $\text{N}_2$ ,  $\text{H}_2$  and  $\text{CO}$  followed by K impregnation. From computational simulations, it appears that  $\text{Fe}_5\text{C}_2$  particles with a small amount of K ( $\sim 1 \text{ wt\%}$ ,  $\text{K/Fe} = 0.05$ ) exhibit facile  $\text{C}_5$ – $\text{C}_8$  olefin dissociation *via* lowering of the chemisorption energy. The K-doped  $\text{Fe}_5\text{C}_2$ @C/NPC showed high FT activity and  $\text{CO}$  conversion ( $\sim 97\%$ ), as well as good selectivity for  $\text{C}_5$ – $\text{C}_{13}$  LAOs with excellent stability. The K promotion led to facile  $\text{CO}$  adsorption and dissociation, which increased the basicity of the active  $\text{Fe}_5\text{C}_2$  surface. The appropriate electronic state derived from the K-doped  $\text{Fe}_5\text{C}_2$  nanoparticles resulted in enhanced selectivity for  $\text{C}_5$ – $\text{C}_{13}$  LAOs along with control of the hydrogenation and desorption rates. In addition, the high load of active Fe ( $\sim 34 \text{ wt\%}$ ) with its uniform dispersion on the nitrogen-doped porous carbon support also contributed to enhanced activity and productivity in HT-FTS. With its enhanced  $\text{CO}$  conversion, reduced induction period and increased



selectivity for C<sub>5</sub>–C<sub>13</sub> LAOs, it is anticipated that the K-doped Fe<sub>5</sub>C<sub>2</sub>@C/NPC nanocatalyst could optimize the sustainable production of valuable LAOs from HT-FTS.

## Author contributions

Jin Hee Lee: FTS experiment and drafting; Hack-Keun Lee: data curation and drafting; Kwangsoo Kim: DFT calculation; Geun Bae Rhim: data curation; Min Hye Youn: investigation; Heon-Do Jeong: visualization; Jong Hyeok Park: visualization; Dong Hyun Chun: conceptualization and editing; Byung-Hyun Kim: computer simulation and writing; Ji Chan Park: conceptualization, methodology and writing.

## Conflicts of interest

There are no conflicts to declare.

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