Achieving efficient and robust catalytic reforming on dual-sites of Cu species†

Kui Ma, Ye Tian, Zhi-Jian Zhao, Qingpeng Cheng, Tong Ding, Jing Zhang, Lirong Zheng, Zheng Jiang, Takayuki Abe, Noritatsu Tsubaki, Jinlong Gong, *ac and Xingang Li, *ab

Catalytic reforming provides a practical technique for on-board hydrogen production in fuel cell applications. The high energy density, easy transportation and non-toxicity of biomass-derived dimethyl ether (bio-DME) offer potential to replace methanol on-board steam reforming (SR). Presently, the reaction mechanism over conventional Cu-based SR catalysts remains elusive, limiting the rational design of highly efficient reforming systems. Herein, we build a catalytic system for bio-DME SR with dual-sites of Cu species, i.e., Cu+ and Cu0 sites, and achieve a record-high H2 production rate of 1145 mol kgCat h−1. Via regulating the ratios of the dual-sites of Cu, we clearly describe molecular understanding on SR. And we discover that the substantially boosted activity is induced by a new Cu+−dual-sites of Cu species, i.e., Cu+ and Cu0 sites, and achieve a record-high H2 production rate of 1145 mol kgCat h−1. Via regulating the ratios of the dual-sites of Cu, we clearly describe molecular understanding on SR. And we discover that the substantially boosted activity is induced by a new Cu+-determined reaction path substituting the conventional Cu0-determined path. Intrinsically, Cu2O can act as a physical spacer and hydroxyl consumer to suppress the aggregation of metallic Cu species in SR. Due to the unique structure of metallic Cu surrounded by Cu2O, the catalyst exhibits robust catalytic performance even after severe thermal treatment. These findings open a new avenue for designing efficient catalytic reforming systems with commercial potential.

Introduction

Hydrogen, a renewable resource with a high energy density (142 MJ kg−1), is consumed today as a chemical raw material (about 5 × 1010 kg per year worldwide).1 As the core of the hydrogen economy, fuel cells running on hydrogen are attractive power supplies for versatile applications.2,3 The required hydrogen comes from a stable on-board production system, ensuring its safe storage and transportation.4,5 Recently, the development of technologies for converting biomass has resuscitated the surge of reforming renewable oxygenated hydrocarbons, e.g., methanol, ethanol, dimethyl ether (DME), and glycerol, with H2O for on-board hydrogen production.6,8 In view of the mild SR conditions, methanol and DME without C=C bonds are the primary choices.9 The usage of DME can release hydrogen with a higher gravimetric density of 26.1 wt% than methanol (18.8 wt%). As the European project BioDME has been industrially built and operated in Sweden, bio-DME is becoming a potential reforming feed to replace the traditional methanol.10,11 The non-toxicity of DME offers another important advantage. DME SR is an integrated technology consisting of hydrolysis of DME to methanol over solid acid catalysts, and subsequently methanol SR over metal catalysts. Currently, γ-Al2O3 is the commonly used acid catalyst for DME hydrolysis operated above 300 °C,12 requiring higher operating temperatures for the following SR. And copper-based catalysts have been intensively explored in reforming reactions with the inherent drawback of thermal deactivation by metal-particle growth.13

It is commonly perceived that Cu0 is primary and indispensable for SR,14,15 bringing debate about the role of Cu+. Some researchers have proposed that Cu+ is active in suppressing the by-product of carbon monoxide (CO) from the reverse water–gas shift, the main side reaction in SR.16–18 However, others still suggest that Cu+ could directly catalyze the steam reforming, and speculate that there may exist an optimum cooperation between Cu0 and Cu+ to boost activities,19–21 but this lacks effective evidence. Currently, Cu+ species are usually introduced through addition of metal oxides to Cu-based catalysts, and self-
redox reaction of copper species under feed and reaction conditions.22–25 The complexity of these systems impairs efforts to identify the exact role of copper. In this regard, copper phyllosilicates \( [\text{Cu}_2\text{Si}_2\text{O}_5(\text{OH})_2]_n \), providing stable Cu species under hydrogen-rich conditions in catalytic hydrogenation,26–28 may be adopted as a controllable Cu-supplier to investigate SR mechanisms. However, the tendency of Cu nanoparticles (NPs) to grow into larger crystallites is an impediment to the stable performance of Cu-based catalysts, especially for those without promoters. Intrinsically below the Tammann temperature of copper (407 °C), the aggregation of Cu NPs is mainly induced by Ostwald ripening occurring across the support surface through the functional groups (e.g., hydroxyl).29 It is another stumbling block in further design of Cu-based catalysts.

This paper describes the design and fabrication of a hierarchical Cu–Si system with dual-sites of Cu species (denoted as Cu-AE) via a vacuum-rotary ammonia evaporation method by employing SBA-15 as the silicon source. The ordered three-dimensional (3D) mesoporous channels of SBA-15 can improve molecular diffusion, and restrict the growth of copper NPs. As described in Fig. 1A, the well-ordered Si–OH sites on SBA-15 and vacuum conditions facilitate the dispersion and uniform arrangement of the Cu species.30 Consequently, CuO nanoparticles (NPs) dispersed into \( \text{Cu}_2\text{Si}_2\text{O}_5(\text{OH})_2 \) nanotubes (NTs) are successfully developed on SBA-15. After reduction, metallic Cu NPs are generated from the CuO NPs, while the CuO NPs are from the surrounding \( \text{Cu}_2\text{Si}_2\text{O}_5(\text{OH})_2 \) NTs. Based on this synthesis mechanism, we tune the dual-sites of copper to quantify their contributions to SR, and achieve a record-high \( \text{H}_2 \) production rate of 1145 mol kg\(^{-1} \)h\(^{-1} \) with the structure of metallic Cu surrounded by CuO. We also discover that the formation of CuO consumes the hydroxyl groups on the support, which retards the Ostwald ripening of metallic Cu, thereby leading to a robust SR performance.

Results and discussion

The TEM images of 25Cu-AE in Fig. 1B–D are obtained to illustrate the synthetic procedure. As indicated by the FTIR and UV-Raman results (Fig. S1†), abundant Si–OH groups (the \( \nu_\text{Si–OH} \) vibration at 958 cm\(^{-1} \)) exist on the SiO\(_4\) tetrahedron-shaped matrix of the mesoporous SBA-15 (Fig. 1B). After ammonia evaporation, the disappearance of the \( \nu_\text{Si–OH} \) vibration band in 25Cu-AE implies that Si–OH groups are consumed during the \( \text{Cu}_2\text{Si}_2\text{O}_5(\text{OH})_2 \) formation. On 25Cu-AE, the NPs are CuO, while the NTs lacking lattice fringes are \( \text{Cu}_2\text{Si}_2\text{O}_5(\text{OH})_2 \) (Fig. 1C).32 This formation mechanism is also applied to the other Cu-AE catalysts with different Cu loadings. The XRD and X-ray absorption near-edge structure (XANES) results also verify the coexistence of \( \text{Cu}_2\text{Si}_2\text{O}_5(\text{OH})_2 \) and CuO in Cu-AE catalysts (Fig. S2†).

Semi-quantitatively, we adopted linear combination fitting (LCF) of the XANES spectra (Fig. S3†) to estimate the contents of \( \text{Cu}_2\text{Si}_2\text{O}_5(\text{OH})_2 \) in the catalysts. It shows a volcano-type behavior following the increase of the Cu content and maximizes at 25Cu-AE (Table S1†). Obviously, in Fig. S4A† CuO NPs are continuously enriched with the increase of the copper content in the catalysts, and eventually cap the \( \text{Cu}_2\text{Si}_2\text{O}_5(\text{OH})_2 \) NTs. From the low-angle XRD patterns in Fig. S5,† all the samples present three well-resolved diffractions at a 2θ of 0.5–3.0, which can be indexed to the ordered hexagonal lattice (p6mm) of SBA-15.33 Noticeably, the diffraction peaks of the Cu-AE catalysts shift to higher angles compared with those of the pristine SBA-15, reflecting a slight contraction of the unit cell. This phenomenon is contributed by the partial destruction of the ordered pore structure of SBA-15 due to the dissolution of silica during the preparation process, as can be directly observed by TEM as shown above. Here, the existence of these characteristic low-angle diffraction peaks of Cu-AE suggests that most of the channels of SBA-15 are still preserved. Furthermore, the Cu-AE catalysts show weaker \( d_{100} \) intensity, indicating that the copper loading in the mesopore channels reduces X-ray diffraction.33,34

Based on the above results, the schematic illustrations of the Cu species distribution with the increased Cu loading are presented in Fig. S4C.† Summarily, the 25Cu-AE possesses the well-proportioned and uniformly arranged \( \text{Cu}_2\text{Si}_2\text{O}_5(\text{OH})_2 \) NTs and CuO NPs.

In the reduced Cu-AE catalysts, both the preserved characteristic diffractions of SBA-15 in low-angle XRD patterns (Fig. S6A†) and the narrowed size distribution of 4.3 nm (Fig. S7†) demonstrate the existence of regular channels. We also observed CuO (JCPDS no. 05-0667) and metallic Cu (JCPDS no. 04-0836) from wide-angle XRD patterns in Fig. S6B† CuO and metallic Cu originate from the reduction of \( \text{Cu}_2\text{Si}_2\text{O}_5(\text{OH})_2 \) and CuO, respectively.27 In particular, the metallic Cu is surrounded by CuO on 25Cu-AE (Fig. 1D), which is due to the appropriate proportion of Cu species in the calcined catalysts (Fig. S4†). Table S2† gives the physicochemical properties of the catalysts, indicating that we can modulate the physicochemical properties of Cu-AE via tuning the Cu loading. Compared with other catalysts, the Cu-AE catalysts possess the smaller Cu crystal sizes and more accessible surface Cu atoms.

We employed \( \text{H}_2 \)-TPR (Fig. 2A) and \( \text{in situ} \) reduction QXAFS (Fig. 2B) to identify the reducibility and copper species of the catalysts. Generally, the reduction of copper phyllosilicates to Cu\(^+\) and highly dispersed CuO to Cu\(^0\) occurs at ca. 247–267 °C.
in the chemical environment and content of surface Cu (Table S3†) are nearly negligible, also suggesting that the equilibrium between Cu⁺ and Cu⁰ over the reduced Cu-AE catalysts is very stable, and is broken with difficulty by the SR reaction. In addition, as summarized in Table S3,† the ratio of Cu⁺/(Cu⁰ + Cu⁰) decreases with the elevated Cu loading, coinciding with the tendency of calculated surface Cu atoms in Table S2.†

Generally, the chemical state of Cu species is sensitive to the environmental atmosphere.³⁷ We performed in situ steady-state XANES to monitor the chemical state of Cu under reaction conditions. As calibrated by the first derivatives of the K-edge XANES spectra in Fig. S11,† the absorption edge at ca. 8980.4 eV of 25Cu-AE in Fig. 2C is located in the middle of those of Cu foil (8979.4 eV) and Cu₂O (8980.9 eV). Combined with the absence of the pre-edge feature at ca. 8977 eV for Cu²⁺ (inset in Fig. 2C),³⁷ we conclude that Cu⁺ species indeed exist in 25Cu-AE and remain stable during the operation. But for 25Cu-IM, its absorption edge location and white line feature are close to Cu foil, indicating the lack of Cu⁺ in the bulk of 25Cu-IM during the reaction. Fig. 2D shows the in situ temperature-resolved XANES spectra of 25Cu-AE. The curves are quite similar in shape at different reaction temperatures, and their absorption edges locate in the middle of those of Cu foil and Cu₂O. These results demonstrate that the copper oxidation state has little change in dynamic reactive atmospheres at different reaction temperatures, in accordance with the XPS results in Fig. S9, S10 and Table S3.† The above comprehensive characterization results demonstrate a successful synthesis of the catalytic system with tuneable and stable dual-sites of Cu species.

We investigated the catalytic performance and stability of the catalysts after 12 h severe thermal treatment (GHSV = 36 000 h⁻¹, T = 450 °C) for DME SR. Table 1 summarizes the performance of the catalysts in a numerical form, and Table S4† lists the activity of the representative catalysts for DME SR and methanol SR. In Table 1, 25Cu-AE exhibits a higher catalytic activity in comparison with others. It achieves a DME conversion of 100%, CO selectivity of ca. 10%, and H₂ yield exceeding 95%, leading to a record-high H₂ production rate of 1145 molH₂/kgcat/h⁻¹ (Table S4†), 6-fold higher than that of commercial Cu/Zn,⁴⁷ The highest TOFₜₘ over 25Cu-AE reaches 0.147 s⁻¹, about 2 and 10 times higher than those of the as-prepared Cu/ZnO/Al₂O₃ and 25Cu-IM, respectively (Table 1). Additionally, 25Cu-IM shows a lower H₂ yield and higher CO selectivity as compared with the Cu-AE catalysts, indicating that the latter’s excellent catalytic activities probably lie in the presence of Cu⁺ species.

Fig. 3A displays the catalytic stability of 25Cu-AE, and Fig. 3B shows the TEM images at the corresponding stages. At stage I prior to the thermal treatment, the activity of 25Cu-AE shows no change while that of 25Cu-SiO₂ drops rapidly as shown in Fig. S12† Intrinsically, unlike the steady Cu NP distribution of ~3.5 nm over 25Cu-AE (Fig. S13A†), the Cu NPs over 25Cu-SiO₂ increase from ~4.1 to ~9.2 nm (Fig. S13B†) after stage I.

As the reaction temperature (400 °C) is relatively lower than the Tammann temperature of copper (407 °C), the thermal migration of copper atoms in the catalysts is difficult in the absence of a reactive adsorbate. Thus, the copper particle
growth in SR is probably mediated by mobile copper adsorbate species on the support (Ostwald ripening). The transport of Ostwald ripening Cu species depends upon the chemical nature of the support surface. As evidenced by FTIR in Fig. S1A,† the formation of copper phyllosilicates is accompanied by consuming surface hydroxyl groups, which is an efficient support functionalization to increase the distance between neighboring functional groups and consequently inhibits Cu⁰ diffusion, as presented in Fig. 3C. Accordingly, the structure of Cu surrounded by Cu₂O in 25Cu-AE maximizes such restriction. Also, Cu₂O NPs can function as a physical spacer to isolate Cu⁰ NPs.

After the thermal treatment (stage II), the DME conversion over 25Cu-AE drops to 84% but remains stable for another 30 h at stage III; meanwhile the TEM images of 25Cu-AE in Fig. 3B demonstrate a break of the surrounding structure of copper species. Herein, a bimodal size distribution of ~11.2 and ~5.8 nm is presented after stage III, which is attributed to the aggregated Cu species on the outer surface and in the channels, respectively (Fig. S13A†). For 25Cu-SiO₂, the catalytic performance substantially decreases at stage III. The corresponding Cu NPs noticeably aggregate as indicated by a distribution of ~15.0 nm after stage III (Fig. S13B†). Thus, we conclude that the spatial restriction by the channels of SBA-15 can also help inhibit the aggregation of Cu⁰ (Fig. 3D). Owing to such combined effects, 25Cu-AE exhibits a robust performance (DME conversion: 83.9%, H₂ yield: 72.7%) even after the severe thermal treatment.

We hypothesize that the high activity of Cu-AE results from a cooperative effect of the unique dual-sites of copper species. To gain more insight into this, the respective contributions from the Cu⁰ and Cu⁺ species are required to be clarified. Thus catalysts containing pure Cu⁰ and Cu⁺ species are desired. However, the Cu⁰ and Cu⁺ always coexist in Cu-AE catalysts. For the above compared 25Cu-IM, its crystal size (29 nm) is much larger and less uniform than those of Cu-AE (<10 nm) (Table S2†). Moreover, the impregnation method inevitably brings the strong metal-support interaction to affect the chemical state and size distribution of copper. Consequently, we introduce a physical-sputtering method to realize a homogeneously distributed metallic Cu nano-catalyst (Cu-SP) instead of 25Cu-IM for rigorous comparison and discussion. For Cu-SP, the
TEM and H₂-TPR results (Fig. S14†) show that the copper NPs mainly exist as Cu⁰, which could be oxidized to Cu₂O by N₂O to obtain Cu-SP-N. Their physicochemical properties are listed in Table S5.†

We quantify the surface density of Cu⁰ and Cu⁺ sites (Tables S2 and S5†) to analyze their contributions toward the reaction. In Fig. 4A, the surface Cu⁰ site density is observed to scale linearly with the formation rates of H₂ (r₁H₂) in group I and II independently, suggesting that the H₂ yield depends on the Cu⁰ density with two different reaction paths, whereas there is no clear correlation between the r₁H₂ and the total Cu density (Fig. 4B). Moreover, the higher superficial Cu⁺/(Cu⁰ + Cu⁺) ratio (>0.50) over the catalysts in group I than that (<0.21) in group II is probably the main reason for their superior performance. Thus, we conclude that Cu⁰ is responsible for H₂ desorption, and sufficient Cu⁺ can accelerate the reaction rate. In Fig. 4C, both the TOF₃DM and TOF₄H₂ show a volcanic correlation with the increased Cu⁺/(Cu⁰ + Cu⁺) ratio, and reach a maximum at a Cu⁺/(Cu⁰ + Cu⁺) ratio equal to 0.50 (25Cu-AE). The activation energies (Eₐ) of the catalysts were calculated and classified into two types in Fig. 4D: the lower value at ca. 125 kJ mol⁻¹ for 10Cu-⁰E, 20Cu-⁰E, 25Cu-AE and 30Cu-⁰E with sufficient Cu⁺ sites (denoted as Cu⁺-suf); and the higher value at ca. 160 kJ mol⁻¹ for 25Cu-IM, Cu-SP and 40Cu-⁰E with sufficient Cu⁰ sites (denoted as Cu⁰-suf). Interestingly, Eₐ dropped from 164.5 to 124.5 kJ mol⁻¹ when the Cu⁰ sites in Cu-SP were oxidized to Cu⁺ by N₂O to obtain Cu-SP-N. These results demonstrate the determinant role of the sufficient Cu⁰ sites for reaction paths. Herein, 30Cu-⁰E follows the same reaction path as the other Cu⁺-suf catalysts, while its r₁H₂ diverged from that of group I in Fig. 4A, which is probably ascribed to the excessive Cu⁺ sites on 30Cu-⁰E for H₂ desorption. Summarily, we propose that there exist two reaction paths, and which to follow is determined by Cu⁺.

Thereafter, we evaluated in situ DRIFTS and temperature programmed surface reaction-mass spectroscopy (TPSR-MS) for methanol SR to validate the role of the copper species in the reaction path. In Fig. 5A, we observe the bands of Cu⁺–OH (methoxyl) (1440 cm⁻¹) over Cu⁺-suf and Cu⁺-OOCH (formate) (1345 cm⁻¹) over Cu⁰-suf, respectively, which is also evidenced by the steady-state TPSR-MS (Fig. 5B and C). This suggests that the methoxy and formate groups on their corresponding catalysts are relatively stable, and their dehydrogenation affects the overall reaction rate. Importantly, dioxomethylene (CH₂O₂) is also detected by TPSR-MS in Fig. 5C. Along with the kinetics and Eₐ discrimination from Fig. 4, these findings demonstrate the different rate-determining steps: methoxy dehydrogenation for Cu⁺-suf and formate dehydrogenation for Cu⁰-suf.

Then we collected time-resolved in situ DRIFTS spectra of 25Cu-⁰E, Cu-SP and Cu-SP-N (Fig. S15–S17, Table S6†) to draw the hypothetical mechanism. Over Cu⁺-suf, we assume that the Cu⁰ sites are responsible for transferring atomic H and hydrogen desorption; and the Cu⁺ sites contributed to adsorbing oxygen-bonded intermediates. From the in situ DRIFTS results in Fig. S15, the catalytic cycle begins with the dissociative adsorption of methanol (1008 and 1033 cm⁻¹) on the surface. Then, dehydrogenation of the methoxy group (1440 and 1423 cm⁻¹) to formaldehyde occurs as the first barrier. Surface hydroxyls (3737 cm⁻¹) immediately attack the formaldehyde, resulting in the formation of dioxomethylene as a reaction intermediate, whereafter, it dehydrogenates into formate groups (1548 and 1600 cm⁻¹) and proceeds to dehydrogenate eventually to CO₂ (2359 and 2327 cm⁻¹), adsorbing in the form of monodentate carbonate species (1463 cm⁻¹). All H atoms produced by dehydrogenation migrate to the Cu⁰ sites through support due to the back spillover, and finally desorb as gaseous H₂. We name it a dual-site reaction path (Fig. 5D). Over Cu⁰-suf in Fig. S16, the adsorption and transition of methanol (1010 and 1050 cm⁻¹), formaldehyde (1736 cm⁻¹), dioxomethylene, formate (1345 and 1577 cm⁻¹) and carbonate (1371 cm⁻¹) occurs on the Cu⁰ sites alone (Fig. S16), consistent with the reported DFT calculations on Cu(111). In this case, H is competitively adsorbed with oxygenated intermediates, thereby readily meeting the second barrier at formate dehydrogenation and inhibiting the overall reaction rate.

Interestingly, in Fig. 5A, monodentate formate (1600 cm⁻¹), considered to be more active in deep dehydrogenation, tends to form on Cu⁺-suf, while both monodentate (1577 cm⁻¹) and bidentate (1345 cm⁻¹) species appear on Cu⁺-suf. Cu⁺ sites may function as the electrophilic sites to readily electrostatically adsorb the negative electron of O=C in formate, thereby forming more active monodentate formate to overcome the formate dehydrogenation barrier. Thus, we intrinsically reveal that the rate-determining step of the dehydrogenation of methoxy or formate relies on the valence state of Cu.

Through the evaluation on a recycle fixed-bed reactor (Fig. S18†), a microkinetic model for methanol SR over 25Cu-⁰E was established to verify the reliability of our proposed dual-site reaction path (see details in the Experimental section of the ESIT). In this model, the competitive adsorption of oxygenates and dissociative adsorption of hydrogen occur on Cu⁺ and Cu⁰ sites, respectively. The dehydrogenation of the methoxy group on Cu⁺ sites is the rate-determining step, and thus all of the other elemental reactions are in thermodynamic equilibrium.
As expected, the experimental data and the dual-site microkinetic prediction are in good agreement (Fig. 5F).

Conclusions

In summary, we have successfully designed a dual Cu reforming system with a record-high and robust H\textsubscript{2} production rate of 1145 mol kg\textsubscript{cat}\textsuperscript{−1} h\textsuperscript{−1}, and provided new insights into the fundamental understanding of Cu-catalyzed SR. In fact, there exist two kinds of distinct rate-determining steps: methoxy dehydrogenation for Cu\textsuperscript{+}-suf and formate dehydrogenation for Cu\textsubscript{0}-suf. Cu\textsuperscript{+} may function as the electrophilic site to adsorb the negative electron of O–C in formate, thereby more readily forming active monodentate formate. This can intrinsically accelerate the overall reaction rates. Moreover, the surrounding Cu\textsubscript{2}O and nano-channels of SBA-15 can inhibit the aggregation of metallic Cu species during SR. Our design provides a commercially achievable reforming system for fuel cells and paves a new way to related reaction mechanism investigations.

Conflicts of interest

The authors declare no conflict of interest.

Author contributions

X. G. L., J. L. G. and K. M. conceived the idea; K. M., J. L. G., Y. T., Z. J. Z., Q. P. C. and T. D. carried out the experiments; N. T. and T. A. prepared the sputtered catalysts; J. Z., L. R. Z. and Z. J. helped collect XAFS data; X. G. L., J. L. G. and K. M. analyzed the experimental data and wrote the manuscript. X. G. L. and J. L. G. supervised the whole project. All authors participated in discussions of the research.

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Notes and references


