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Mechanism of methanol steam reforming with inverse ZrO₂/Cu catalyst

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The highly active inverse ZrO₂/Cu catalyst used in methanol steam reforming reaction was confirmed by XRD and HRTEM. Control experiments and characterization results consistently differentiated surface and interfacial hydroxyl groups. For the catalyst enriched in interfacial OH, the reaction preferentially proceeded through the formate pathway. However, for the catalyst enriched in surface OH, methyl formate pathway preferentially existed on its surface. This work reveals the role of OH plays in the methanol steam reforming reaction, preliminarily establishing foundation for the investigation of H₂O-participated reactions.

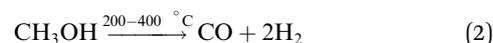
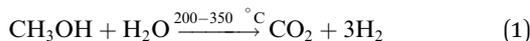
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1 Introduction

Hydrogen energy, as a clean and renewable energy source, plays a crucial role in resolving the global energy crisis and mitigating environmental challenges. However, its widespread application is currently restrained by issues such as storage safety risks, high transportation costs, and the difficulty of hydrogen production.^{1,2} In contrast, methanol, with a high hydrogen content of up to 12.5 wt% and relatively safe transport properties, has emerged as a promising carrier for hydrogen storage and transportation.^{3–7} The hydrogen stored in methanol can be efficiently released *via* the methanol steam reforming (MSR) reaction (eqn (1)). Nevertheless, side reaction occurring during the MSR process (eqn (2)) decreases hydrogen impurity, which significantly hinders its practical utilization. Therefore, the development of high efficient MSR catalyst and the comprehensive understanding of the MSR mechanism is of great importance.^{1,8,9}



MSR reaction is a complex, multi-step process including the steps such as methanol dehydrogenation, hydroxyl dissociation, and the water–gas shift reaction.¹⁰ The reaction mechanism is commonly proposed to proceed *via* three primary pathways: (1) methanol undergoes dehydrogenation to form formaldehyde, which subsequently decomposes into carbon monoxide and hydrogen; carbon monoxide then reacts with water through the water–gas shift reaction, yielding carbon dioxide and hydrogen.¹¹ (2) Methanol dehydrogenates to generate methoxy species, which react with methanol to produce methyl formate; methyl formate subsequently decomposes into formate species, which further decompose into carbon dioxide and hydrogen.¹² (3) Methanol dehydrogenates to form formaldehyde, which is oxidized by water to form formic acid; formic acid then decomposes into carbon dioxide and hydrogen.¹³ Hence, a comprehensive investigation of the reaction mechanism, particularly the structure–function relationships of active sites, is essential for enhancing the efficiency and selectivity of the reaction.¹⁴ Such insights also provide a scientific basis for the rational design of catalysts, facilitating industrial-scale applications.

In our previous work, we have developed an effective inverse ZrO₂/Cu (ZrO₂: ~2–3 nm, Cu: ~10–15 nm) for the MSR reaction.¹⁵ The work mainly investigated the adsorption and desorption of the intermediates such as HCHO, HCOOCH₃. Additionally, traditional Cu/ZrO₂ or inverse ZrO₂/Cu have also been reported in the MSR reaction by other groups and the effects (such as the pivotal intermediate HCOO–Cu,¹⁶ Cu size,¹⁷ Cu valence,¹⁷ and ZrO₂ crystal phase¹⁸) have been investigated. However, the role of hydroxyl species playing in MSR reaction is still unclear. Moreover, the hydroxyl species plays an important

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role in H₂O-related reactions, such as MSR reaction,¹⁹ water gas shift reaction,²⁰ and CO preferential oxidation reactions.²¹ This work reveals that on the ZrO₂/Cu catalyst, the surface OH (on ZrO₂ surface) and interfacial OH (at ZrO₂-Cu interface) coexist, the interfacial OH being more active in the MSR reaction. *In situ* diffuse reflectance infrared fourier-transform spectroscopy (*in situ* DRIFTS) confirmed that methanol adsorbed on surfaces rich in interfacial hydroxyl groups undergoes the formate pathway,²² leading to the formation of CO₂ and H₂ (CH₃OH + interfacial OH → CH₃O*, CH₃O* + interfacial OH → HCOOH → CO₂ + H₂O). In contrast, on surfaces with surface hydroxyl groups, which react with methanol to produce *COOH. Subsequently, *COOH reacts with CH₃OH to form methyl formate. Finally, methyl formate decomposes to CH₃O* (CH₃O* transform to formate to accomplish catalytic cycle) (CH₃OH + surface OH → *COOH, *COOH + CH₃OH → HCOOCH₃ → CH₃O*, CH₃O* + minor interfacial OH → HCOOH → CO₂ + H₂O). This reaction mechanism highlights the critical role of hydroxyl groups in determining catalytic performance, establishing the foundation of developing high performance MSR catalysts.

2 Experimental

The detailed catalyst preparation, catalyst characterization, and catalyst evaluation (Fig. S1) were exhibited in the SI. Note that: fresh ZrO₂-0.25/Cu (weight content of ZrO₂ was 25%) without other pre-treatment condition, the sample was abbreviated as ZrO₂-0.25/Cu-dried. For the fresh ZrO₂-0.25/Cu under (H₂O-bubbling atmosphere H₂O bubbling in He flow (30 mL min⁻¹) for 30 min), the sample was labelled as ZrO₂-0.25/Cu-humidified. For the fresh ZrO₂-0.25/Cu after reduced (H₂/He mixed gas (5 vol% H₂)) for 30 min, (300 °C), the sample was named as ZrO₂-0.25/Cu-reduced.

3 Results and discussion

3.1 Structures and chemical states of catalysts

In our previous work, we found that ZrO₂-0.1/Cu exhibited excellent catalytic performance in MSR reaction (~60% methanol conversion and 100% CO₂ selectivity at 250 °C).¹⁵ However, for this catalyst, we found that the OH species couldn't be detected by *in situ* DRIFTS. Hence, ZrO₂-0.25/Cu (the weight content of ZrO₂ was 0.25) was selected to investigate the role of OH species playing in this reaction (ZrO₂-0.25/Cu exhibited ~60% methanol conversion and 100% CO₂ selectivity at 250 °C, Fig. S2). XRD pattern (Fig. 1A) revealed that only characteristic diffraction peaks of CuO phase were detected, with the most prominent peak intensity observed for the (111) crystal plane. Notably, no characteristic diffraction peaks of ZrO₂ were identified. Subsequent quantitative analysis of ZrO₂ loading through ICP-OES (Table S1) demonstrated that ZrO₂ loading of 22.01 wt% in the ZrO₂-0.25/Cu catalyst. This finding aligns with the absence of ZrO₂ crystalline phase detection in XRD patterns, indicating that ZrO₂ exists in a highly dispersed state on the CuO surface,²³ which is consistent with our previous studies.¹⁵ To investigate the surface morphology of the catalyst,

transmission electron microscopy (TEM) analysis was performed (Fig. 1B). Distinct lattice fringes with spacings of 0.254 nm and 0.294 nm were clearly observed on the ZrO₂-0.25/Cu surface, corresponding to the (111) plane of CuO and the (011) plane of tetragonal ZrO₂ (*t*-ZrO₂), respectively.²⁴ This observation further confirms the uniform dispersion of fine ~3–4 nm *t*-ZrO₂ particles on the ~10–15 nm CuO substrate in the ZrO₂-0.25/Cu catalyst, rather than the absence of *t*-ZrO₂ components.²⁵ Moreover, for the reduced catalyst, XRD and TEM techniques (Fig. 1A and C) indicated that the ZrO₂/CuO composite transforms to ZrO₂/Cu (ZrO₂, 3–4 nm, Cu 15–20 nm; ZrO₂ and Cu particle size derived from Scherrer equation are 3.5 and 16 nm, respectively), which may play an important role in the MSR reaction. The well-defined lattice structures and interfacial characteristics align with previous reports on Cu/ZrO₂ heterojunction systems, where such structural configurations enhance catalytic performance through synergistic effects.

3.2 Distinguish surface OH from interfacial OH

Derived from previous works, OH plays an important role in the H₂O-related reactions,²⁶ but the surface and interfacial OH hasn't been investigated. From these previous works, we know that H₂-reduction or H₂O (D₂O)-bubbling are two vital roles to introduce OH (OD) into the catalyst. So, ZrO₂-0.25/Cu-dried, ZrO₂-0.25/Cu-humidified, and ZrO₂-0.25/Cu-reduced were tentatively investigated by H₂O-TPD to investigate the surface and interfacial OH (Fig. 2). H₂O-TPD profiles reveal two characteristic desorption regions: peak at 180–200 °C corresponding to active interfacial hydroxyl groups (at ZrO₂/Cu interface), and those near 340 °C representing weakly active surface hydroxyl species (on ZrO₂ surface).²⁷ Notably, the ZrO₂-0.25/Cu-dried exhibited a minor concentration of hydroxyl groups, probably contributing to its negligible catalytic activity (~1% methanol conversion at 250 °C). Meanwhile, the ZrO₂-0.25/Cu-humidified shows substantially quantities of surface hydroxyl groups, likely corresponding with its inferior catalytic activity (~5% methanol conversion at 250 °C). Remarkably and interestingly, for ZrO₂-0.25/Cu-reduced, apart from the surface hydroxyl groups at 340 °C, the prominent H₂O-desorption peak at 180–200 °C appeared, tentatively attributed to interfacial OH and corresponding with its excellent catalytic activity (~60% methanol conversion at 250 °C).

Subsequently, CH₃OH-adsorbed ZrO₂-0.25/Cu-dried, ZrO₂-0.25/Cu-humidified, and ZrO₂-0.25/Cu-reduced at different temperatures were investigated by *in situ* DRIFTS to differentiate surface from interfacial OH (Fig. 3). The absorption bands at 3650–3550 cm⁻¹ are attributed to isolated hydroxyl groups on the zirconia surface, those at 3700–3650 cm⁻¹ correspond to surface hydroxyl groups on zirconia,²⁸ and those at 3750–3700 cm⁻¹ are associated with interfacial hydroxyl groups between zirconia and copper, predominantly in the form of Zr-(OH)-Cu.²⁹ For ZrO₂-0.25/Cu-dried, the interfacial hydroxyl group content is nearly absent (Fig. 2). At 175 °C, as methanol enters the reaction, the hydroxyl groups undergo transformations. Upon methanol introduction, methanol undergoes decomposition on the zirconia surface, generating methoxy and



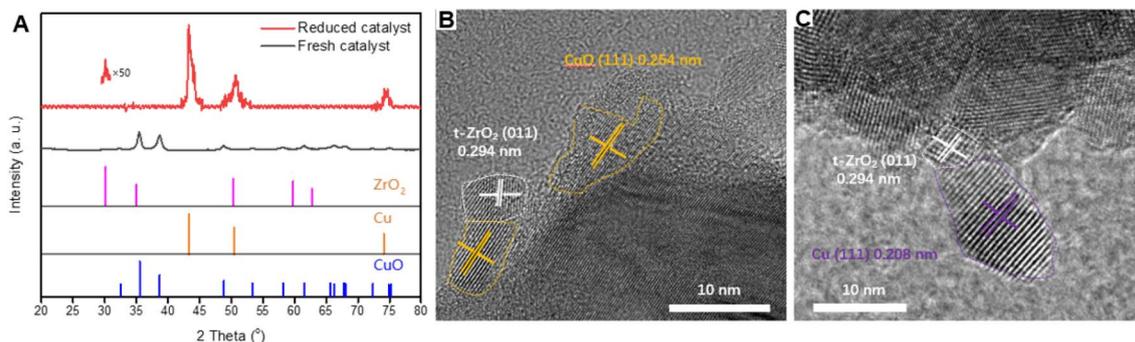


Fig. 1 (A) XRD patterns of fresh $\text{ZrO}_2\text{-}0.25/\text{Cu}$ and $\text{ZrO}_2\text{-}0.25/\text{Cu}$ -reduced; (B) HRTEM image of fresh $\text{ZrO}_2\text{-}0.25/\text{Cu}$; (C) HRTEM image of $\text{ZrO}_2\text{-}0.25/\text{Cu}$ -reduced.

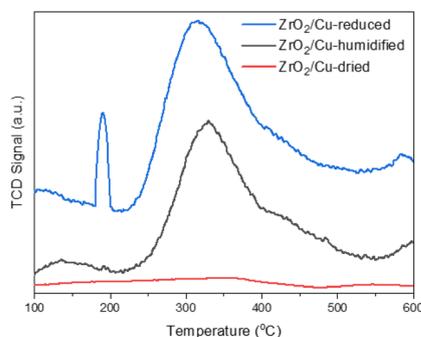


Fig. 2 H_2O -TPD profiles of ZrO_2/Cu -reduced, ZrO_2/Cu -humidified, and ZrO_2/Cu -dried.

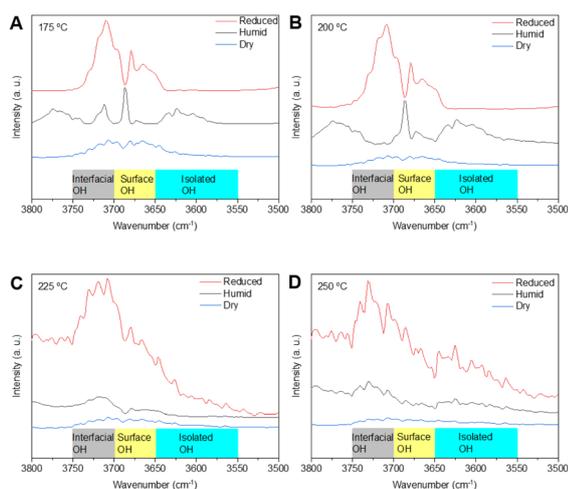


Fig. 3 Amplified *in situ* DRIFTS ($3800\text{--}3500\text{ cm}^{-1}$, to differentiate surface OH from interfacial OH) of ZrO_2/Cu -reduced, ZrO_2/Cu -humidified, and ZrO_2/Cu -dried after methanol reaction for 3 min at different temperatures ((A) $175\text{ }^\circ\text{C}$, (B) $200\text{ }^\circ\text{C}$, (C) $225\text{ }^\circ\text{C}$, (D) $250\text{ }^\circ\text{C}$).

hydrogen species. The hydrogen (from OH of CH_3OH) preferentially reacts with surface oxygen to form surface hydroxyl groups (Fig. 3). The minimal amount of carbon dioxide detected (corresponding to the $\text{C}=\text{O}$ stretching vibration at 2360 cm^{-1}) indicates low activity of these surface hydroxyl groups (Fig. 4). In

contrast, for $\text{ZrO}_2\text{-}0.25/\text{Cu}$ -humidified, due to the presence of water, it exhibits a substantial amount of surface hydroxyl groups with minor interfacial hydroxyl groups (Fig. 3), corresponding with its moderate CO_2 production (Fig. 4). For $\text{ZrO}_2\text{-}0.25/\text{Cu}$ -reduced, the catalyst surface contains a significant amount of interfacial hydroxyl groups (Fig. 3), leading to an unusually high CO_2 yield (Fig. 4). Notably, with the increasing of temperature ($175\text{--}250\text{ }^\circ\text{C}$), surface OH transforms to interfacial OH, forming the active $\text{Zr}(\text{OH})\text{-Cu}$ structure (can be observed for $\text{ZrO}_2\text{-}0.25/\text{Cu}$ -humidified and obviously found for $\text{ZrO}_2\text{-}0.25/\text{Cu}$ -reduced). Hence, the interfacial OH plays an important role in MSR reaction and a part of surface OH could transform to interfacial OH.

3.3 Reaction mechanism

In the MSR reaction, H_2O can dissociate at the surface or the interface site to form OH species.³⁰ For $\text{ZrO}_2\text{-}0.25/\text{Cu}$ -dried, with the increase of temperature from $175\text{ }^\circ\text{C}$ to $250\text{ }^\circ\text{C}$, the $\text{C}=\text{O}$ stretching vibrations of methyl formate (Fig. 5, at 1740 and

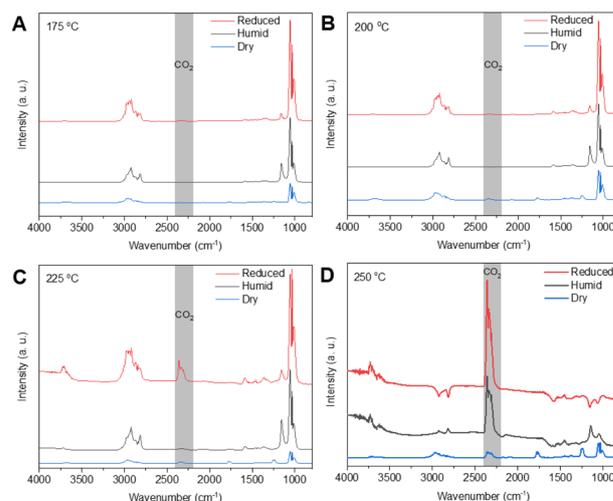


Fig. 4 Amplified *in situ* DRIFTS ($4000\text{--}900\text{ cm}^{-1}$, to differentiate CO_2) of ZrO_2/Cu -reduced, ZrO_2/Cu -humidified, and ZrO_2/Cu -dried after methanol reaction for 3 min at different temperatures ((A) $175\text{ }^\circ\text{C}$, (B) $200\text{ }^\circ\text{C}$, (C) $225\text{ }^\circ\text{C}$, (D) $250\text{ }^\circ\text{C}$).



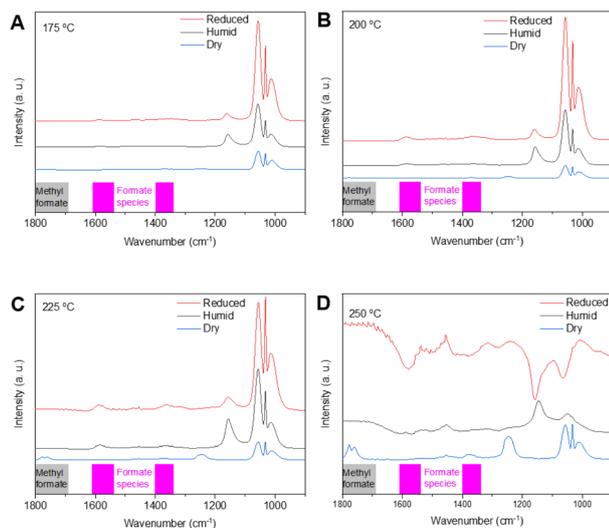


Fig. 5 Amplified *in situ* DRIFTS (1800–900 cm^{-1} , to differentiate methyl formate from formate species) of ZrO_2/Cu -reduced, ZrO_2/Cu -humidified, and ZrO_2/Cu -dried after methanol reaction for 3 min at different temperatures ((A) 175 °C, (B) 200 °C, (C) 225 °C, (D) 250 °C).

1780 cm^{-1}) increase progressively.²³ Meanwhile, no significant change attributed to surface OH is observed in the peak region at 3700–3650 cm^{-1} (Fig. 3), and the peak at 2360 cm^{-1} assigned as CO_2 (Fig. 4) is considerably lower compared to the other two samples. These observations consistently suggest that in the

absence of interfacial hydroxyl groups, the reaction preferentially proceeds *via* the methyl formate pathway (Fig. 6A), resulting in low catalytic activity. For $\text{ZrO}_2\text{-}0.25/\text{Cu}$ -humidified and $\text{ZrO}_2\text{-}0.25/\text{Cu}$ -reduced, interfacial hydroxyl groups coexist on the catalyst surface. However, $\text{ZrO}_2\text{-}0.25/\text{Cu}$ -reduced exhibits a higher interfacial hydroxyl content. With the increase of temperature from 175 to 250 °C, formate species (at 1580 and 1380 cm^{-1} , corresponding to the asymmetric and symmetric COO) is appeared (Fig. 5), with the intensity of $\text{ZrO}_2\text{-}0.25/\text{Cu}$ -reduced being higher.³¹ Meanwhile, CO_2 content displays a relatively higher content (Fig. 4). These findings indicate that, in the presence of interfacial hydroxyl groups, the reaction proceeds through the formate pathway (Fig. 6B), leading to significantly enhanced catalytic activity. For $\text{ZrO}_2\text{-}0.25/\text{Cu}$ -dried, with the increase of temperature from 175 °C to 250 °C, the C=O stretching vibrations of methyl formate (Fig. 5, at 1740 and 1780 cm^{-1}) increase progressively.²⁰ Meanwhile, no significant change attributed to surface OH is observed in the peak region at 3700–3650 cm^{-1} (Fig. 3), and the peak at 2360 cm^{-1} assigned as CO_2 (Fig. 4) is considerably lower compared to the other two samples. These observations consistently suggest that in the absence of interfacial hydroxyl groups, the reaction proceeds *via* the methyl formate pathway (Fig. 6A), resulting in low catalytic activity. For $\text{ZrO}_2\text{-}0.25/\text{Cu}$ -humidified and $\text{ZrO}_2\text{-}0.25/\text{Cu}$ -reduced, interfacial hydroxyl groups coexist on the catalyst surface. However, $\text{ZrO}_2\text{-}0.25/\text{Cu}$ -reduced exhibits a higher interfacial hydroxyl content. With the increase of temperature from 175 to 250 °C, formate species (at 1580 and

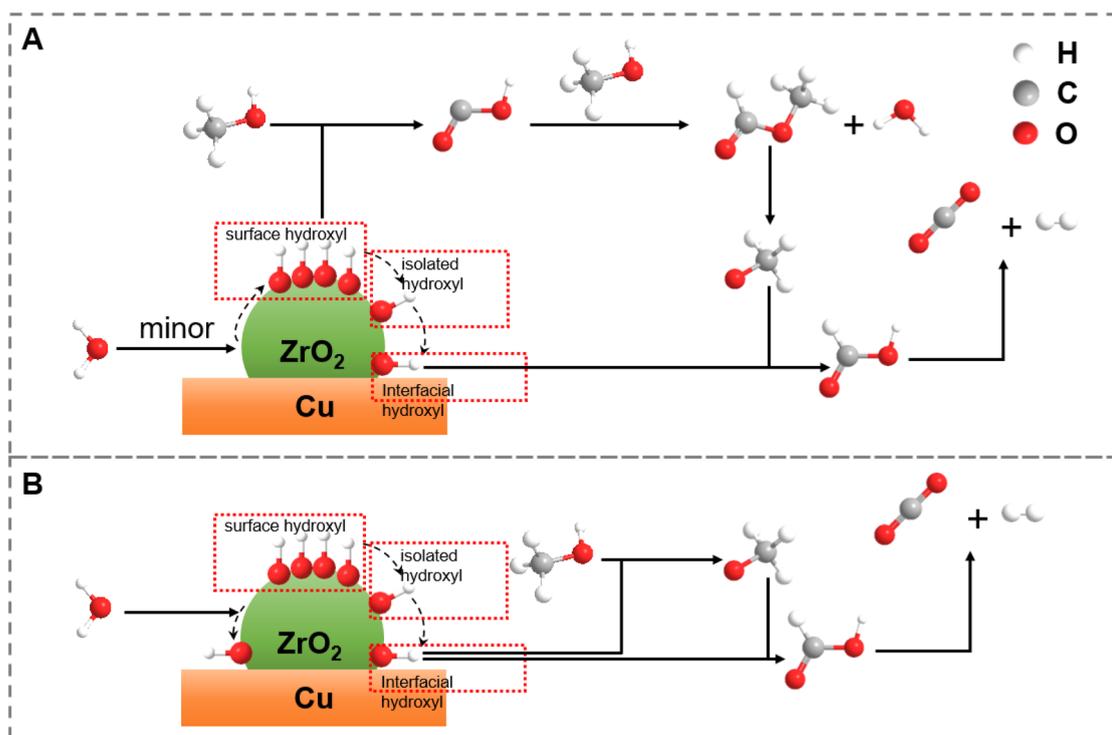


Fig. 6 Reaction mechanism of MSR reaction on ZrO_2/Cu . (A) Catalyzed by surface OH through methyl formate pathway; $\text{CH}_3\text{OH} + \text{surface OH} \rightarrow * \text{COOH}$, $* \text{COOH} + \text{CH}_3\text{OH} \rightarrow \text{HCOOCH}_3 \rightarrow \text{CH}_3\text{O}^*$, $\text{CH}_3\text{O}^* + \text{minor interfacial OH} \rightarrow \text{HCOOH} \rightarrow \text{CO}_2 + \text{H}_2\text{O}$ (B) catalyzed by interfacial OH *via* formate species pathway; $\text{CH}_3\text{OH} + \text{interfacial OH} \rightarrow \text{CH}_3\text{O}^*$, $\text{CH}_3\text{O}^* + \text{interfacial OH} \rightarrow \text{HCOOH} \rightarrow \text{CO}_2 + \text{H}_2\text{O}$.



1380 cm⁻¹, corresponding to the asymmetric and symmetric COO) is appeared (Fig. 5), with the intensity of ZrO₂-0.25/Cu-reduced being higher.²⁷ Meanwhile, CO₂ content displays a relatively higher content (Fig. 4). These findings indicate that, in the presence of interfacial hydroxyl groups, the reaction preferentially proceeds through the formate pathway (Fig. 6B), leading to significantly enhanced catalytic activity.

3.4 Discussion

Moreover, in order to further corroborate the pivotal role of interfacial OH playing in MSR reaction, the control experiments were designed. From the H₂O-TPD experiment, we know that the peaks at ~200 and ~300–400 °C are attributed to the removal of interfacial and surface OH (Fig. 2). Hence, we treated the ZrO₂/Cu-reduced under pure He flow at 180 °C to partly remove the interfacial OH. From Fig. S4, with the treatment time from 1 to 5 min, the peaks (at ~200 °C) corresponding to interfacial OH decrease suddenly and the ones corresponding to surface OH (at 300–400 °C) are nearly unchanged. Meanwhile, the He-treated ZrO₂/Cu-reduced (He: 1, 5 min) could also catalyze methanol steam reforming reaction at 180 °C just using the residual interfacial OH (200 mg catalyst, N₂ flow of 30 mL min⁻¹, and methanol of 1 g h⁻¹). The initial methanol conversions using the ZrO₂/Cu-reduced, ZrO₂/Cu-reduced-He-1 min (ZrO₂/Cu-reduced treated under He flow for 1 min at 180 °C), and ZrO₂/Cu-reduced-He-5 min (ZrO₂/Cu-reduced treated under He flow for 5 min at 180 °C) catalyst were 7%, 2%, 1%, respectively, corresponding well with the H₂O-TPD spectra. Hence, the control experiment further testifies the pivotal role of interfacial OH other than surface OH playing in this reaction.

Up to date, most endeavors are focused on Cu-based catalysts, especially Cu–ZrO₂, because of their attractive low-temperature MSR activity and its substantial potential against CO formation.¹⁵ For example, Ritzkopf *et al.*³² prepared a nano-Cu/ZrO₂ catalyst by the micro-emulsion method, achieving a lower CO selectivity of below 0.1 vol% at 300 °C with a hydrogen productivity comparable to the commercial Cu/ZnO catalyst. Indeed, in the whole process, for our inverse ZrO₂/Cu and Cu/ZrO₂,³² catalysts, the CO selectivity is very low. Thus, we confidently believe that the Cu–ZrO₂ interface is beneficial to the formation of CO₂ other than CO (both inverse ZrO₂/Cu and traditional Cu/ZrO₂ interface) at low temperature (<300 °C). From the H₂O-TPD results (Fig. S5), we could see that for the traditional Cu/ZrO₂,³² the content of interfacial OH is similar to that of our inverse ZrO₂/Cu, so, our inverse ZrO₂/Cu exhibits similar activity (250 °C, 60% methanol conversion and 99.9% CO₂ selectivity) compared with that of traditional Cu/ZrO₂ (250 °C, 58% methanol conversion and 99.9% CO₂ selectivity³²).

4 Conclusion

Through H₂O-TPD and *in situ* DRIFTS analyses, we identified that MSR reaction preferentially proceeds through the formate pathway on the highly active ZrO₂-0.25/Cu-reduced catalyst enriched with interfacial hydroxyl groups. However, for ZrO₂-0.25/Cu-dried, methyl formate pathway preferentially exists on

its surface, due to the existence of surface hydroxyl groups (absence of interfacial hydroxyl groups). These findings provide a novel perspective for the design of metal–oxide model catalysts, offering valuable insights to accelerate the industrial application of such systems.

Conflicts of interest

The authors declare that there is no conflicts of interest.

Data availability

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Supplementary information (SI): the details of catalyst preparation, catalyst characterization, catalyst evaluation, IR flowchart, and H₂O-TPD. See DOI: <https://doi.org/10.1039/d5ra07097j>.

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