Highly Dispersed and Stable Ni/SBA-15 Catalyst for Reverse Water-Gas Shift Reaction

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Abstract: A 1%Ni/SBA-15(P) catalyst was synthesized with a P123-assisted impregnation method, which exhibited high CO₂ conversion and stability in the reverse water-gas shift reaction. For the 1%Ni/SBA-15(P) catalyst, TEM and TPR characterizations demonstrated that the highly dispersed NiO particles at about 3 nm strongly interacted with the SiO₂ support. During reverse water-gas shift reaction, the 1%Ni/SBA-15(P) catalyst exhibited higher CO₂ conversion than the 1%Ni/SBA-15 catalyst prepared by the conventional impregnation method without P123. The CO₂ conversion of the 1%Ni/SBA-15(P) catalyst at 700 °C was 33.7%, which was three times that of the 1%Ni/SBA-15 catalyst. Moreover, the former catalyst was stable at 700 °C within 1000 min. The good activity and stability of the 1%Ni/SBA-15(P) catalyst was owing to small Ni particles that strongly interacted with SBA-15.

Keywords: reverse water-gas shift reaction; Ni; P123; CO₂ conversion

1. Introduction

CO₂ may be utilized through the dry reforming of methane [1–3] and reverse water-gas shift reaction (RWGS) [4–6], which are promising models for CO production. CO can be used as a co-reactant for petrochemical manufacturing (syn-gas for Fischer-Tropsch synthesis, hydroformylation, carbonylation) [7,8]. The RWGS can produce CO from the greenhouse gas carbon dioxide and green hydrogen produced by renewable energy. Nickel-based catalysts show good activity in RWGS [9–12]. However, the side reactions of CO₂ methanation are prone to occur on nickel catalysts [10,12,13]. Highly dispersed small Ni particles are favorable for RWGS, while large Ni particles easily generate methane [14]. The endothermic RWGS reaction has a higher equilibrium conversion at high temperature. In addition, because methanation reaction is exothermic, high temperature is beneficial to inhibit methane formation and improve CO selectivity. However, as highly dispersed Ni is prone to sintering deactivation in the high temperature reaction, it is desired to prepare stable Ni-based RWGS catalysts with high Ni dispersion.

Mesoporous silica-based materials are widely used in catalysis [15–17]. The SBA-15 has been widely used as the support of various highly dispersed catalysts [18–20]. Ni/SBA-15 catalysts have been used for many reactions, such as CO methanation [21], CO₂ methanation [22], CO₂ reforming of methane [23], ethanol steam reforming [24], and glycerol steam reforming [25]. Although the low Ni content of Ni/SBA-15 is beneficial to improve the selectivity of RWGS reaction, low Ni content will result in a lower CO₂ conversion [26].

In this work, the 1%Ni/SBA-15(P) catalyst was synthesized with the P123-assisted impregnation method. Compared with the conventional 1%Ni/SBA-15 catalyst, the
1\%Ni/SBA-15(P) catalyst had smaller NiO particles that interact with SiO$_2$, which were active and stable in the RWGS reaction.

2. Materials and Methods

2.1. Catalyst Preparation

The SBA-15 was synthesized according to the literature [27]. The 1\%Ni/SBA-15(P) catalyst was synthesized by the P123-assisted impregnation method [28,29]. Briefly, 0.050 g nickel nitrate hexahydrate and 0.010 g P123 (n(P123):n(Ni) = 1:100) were added to 20 mL deionized water. After stirring the solution for 1 h, 1 g of SBA was added and then stirred for 12 h. The solution was heated at 60 °C for 3 h and 110 °C for 2 h. Finally, the 1\%Ni/SBA-15(P) catalyst was prepared by the calcination the sample at 600 °C for 4 h.

For comparison, the 1\%Ni/SBA-15 was synthesized by the impregnation method without using P123. In the 1\%Ni/SBA-15 and 1\%Ni/SBA-15(P) catalysts, the nominal content of nickel was 1 wt%.

2.2. Catalyst Characterization

Nitrogen adsorption-desorption analysis was performed on a Quantachrome Autosorb-iQ analyzer at −196 °C (Quantachrome Corporation, Boynton Beach, FL, USA). The sample was degassed at 300 °C for 10 h before analysis. The pore size distribution was obtained using the BJH model. The morphology of the samples was determined by a Tecnai G2 F20 (FEI company, Hillsboro, OR, USA) transmission electron microscope (TEM). The powder X-ray diffraction (XRD) patterns were collected on a DX-2700 X-ray diffractometer (Haoyuan Instrument Co., Ltd., Dandong, China) with Cu K$_\alpha$ radiation at 40 kV and 30 mA. H$_2$ temperature programmed reduction (H$_2$-TPR) measurements were performed on TP-5080 equipment from room temperature to 900 °C (10 °C / min) in 5% H$_2$/Ar (30 mL/min).

2.3. Catalytic Test

Hydrogenation of CO$_2$ was conducted under atmospheric pressure in a fixed bed reactor. Prior to each test, 0.005 g of catalyst and 0.010 g quartz sand were packed in the quartz reactor, and the catalyst was reduced to 650 °C for 2 h under 70% H$_2$/N$_2$ (70 mL/min) flow. When the temperature dropped to 500 °C, the mixed gases (CO$_2$/H$_2$ = 1:1, 100 mL/min) were fed into the reactor for the reaction. The gases product was analyzed by a gas chromatography (GC-7900, Techcomp, Kowloon, Hong Kong). Only CO, CH$_4$, and H$_2$O were produced during the catalytic reaction, and no C2+ hydrocarbon was detected by the GC TCD detector, which was also confirmed by a GC FID detector. Therefore, the conversion and selectivity were estimated as follows:

$$\text{CO}_2\text{ conversion} = \frac{F_{\text{in, CO}_2} - F_{\text{out, CO}_2}}{F_{\text{in, CO}_2}} \times 100\% \quad (1)$$

$$\text{CO selectivity} = \frac{F_{\text{out, CO}}}{F_{\text{out, CO}} + F_{\text{out, CH}_4}} \times 100\% \quad (2)$$

where $F_{\text{in}}$ and $F_{\text{out}}$ stand for the input and output flow rates.

3. Results and Discussion

3.1. Catalyst Characterization

All the N$_2$ adsorption-desorption isotherms in Figure 1a were type IV isotherms with a hysteresis loop, which confirmed the uniform mesoporous structure of the samples. As shown in Figure 1b, the pore sizes of all the samples were similar, indicating that the mesoporous structure did not change after adding Ni to SBA-15. Table 1 shows that the BET specific surface area decreased with the addition of Ni into SBA-15, while the pore volume was almost unchanged.
specific surface area decreased with the addition of Ni into SBA-15, while the pore volume size distribution (cm3 g−1 nm−1)
(b)
Pore diameter (nm)
SBA-15
1%Ni/SBA-15
1%Ni/SBA-15 (P)

Table 1. Physicochemical properties of catalysts.

| Samples | BET Surface Area (m² g⁻¹) | Pore Volume (cm³ g⁻¹) |
|---------|---------------------------|----------------------|
| SBA-15  | 690                       | 1.12                 |
| 1%Ni/SBA-15(P) | 564                  | 1.15                 |
| 1%Ni/SBA-15  | 581                  | 1.13                 |

Transmission electron microscope (TEM) images in Figure 2 show that both catalysts had the ordered mesoporous structures. As shown in Figure 2a,b, the surface of the 1%Ni/SBA-15 catalyst was covered with NiO particles of 40–60 nm. Meanwhile, there were no large NiO particles in the 1%Ni/SBA-15(P) catalyst (Figure 2c), indicating that small NiO was highly dispersed in the nanochannel of SBA-15. As shown in Figure 2d, small NiO particles about 3 nm in size were observed in the HR-TEM image of 1%Ni/SBA-15(P).

Figure 2. TEM images of fresh catalysts: (a,b) 1%Ni/SBA-15 and (c,d) 1%Ni/SBA-15(P).

The small-angle XRD patterns of the fresh and reduced catalysts in Figure 3a showed three typical peaks, which indexed to a hexagonal lattice of mesoporous SBA-15 [30]. The results indicate that all the catalysts possessed the ordered mesoporous structure. After reduction, angles of all reflection planes were moved toward higher angle, implying that d-spacing of SBA-15 support must have been contracted.
The reduced catalysts were treated with 70% H₂/N₂ at 650 °C for 2 h. NiO and Ni peaks were observed in the fresh and reduced 1%Ni/SBA-15 samples, respectively. On the contrary, there was no peak assigned to NiO in the 1%Ni/SBA-15(P), indicating that the NiO particles were highly dispersed in the 1%Ni/SBA-15(P) [28]. No peak assigned to Ni in the reduced 1%Ni/SBA-15(P) indicates that no large Ni particle was formed, even after reduction at 650 °C.

Figure 4 shows the H₂-TPR profiles of the two catalysts. The 1%Ni/SBA-15 had a sharp peak mainly located at 420 °C, assigned to the reduction peak of large particles of NiO [31,32]. The broad reduction peak of the 1%Ni/SBA-15(P) catalyst was between 300–650 °C, and the reduction peak of more than 500 °C was attributed to the reduction of highly dispersed NiO, which had a strong interaction with the SiO₂ [31,33–36]. The TPR results show that Ni was strongly interacted with the support of SiO₂ in the 1%Ni/SBA-15(P) [21,37].

As shown in Figure 3b, the broad peak at about 22° was assigned to the SiO₂ in SBA-15 [24]. The reduced catalysts were treated with 70% H₂/N₂ at 650 °C for 2 h. NiO and Ni peaks were observed in the fresh and reduced 1%Ni/SBA-15 samples, respectively. On the contrary, there was no peak assigned to NiO in the 1%Ni/SBA-15(P), indicating that the NiO particles were highly dispersed in the 1%Ni/SBA-15(P) [28]. No peak assigned to Ni in the reduced 1%Ni/SBA-15(P) indicates that no large Ni particle was formed, even after reduction at 650 °C.

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3.2. Catalytic Performance

The catalytic results are shown in Figure 5. The CO₂ conversion and CO selectivity of the two catalysts increased gradually with the increase of temperature. The 1%Ni/SBA-15(P) catalyst showed higher CO₂ conversions than the 1%Ni/SBA-15 catalyst at the same temperature. The CO₂ conversion of the 1%Ni/SBA-15(P) catalyst at 700 °C was 33.7%, which was three times that of the 1%Ni/SBA-15 catalyst. Because methanation is an exothermic reaction, low temperatures are more conducive to producing methane on the basis of thermodynamics. The CO selectivity of the 1%Ni/SBA-15(P) catalyst was 96.7% at
500 °C, and it increased to 99.8% at 700 °C. Combined with characterization results, the high activity of 1%Ni/SBA-15(P) was due to the small nickel particles in the catalyst.

Figure 5. The catalytic performances of 1%Ni/SBA-15 and 1%Ni/SBA-15(P) catalysts in the RWGS reaction: (a) CO2 conversion, (b) CO selectivity.

The stability study of the 1%Ni/SBA-15(P) catalyst is shown in Figure 6. The CO2 conversion was about 35%, and the CO selectivity was higher than 99.8% during 1000 min. The catalytic results show that the 1%Ni/SBA-15(P) catalyst was stable in the RWGS reaction at 700 °C. Combined with characterization results, the excellent stability should be attributed to the confined effect of SBA-15. The mesoporous confinement and metal-support interaction [38] can enhance the thermal stability of the nickel particles and inhibit sintering.

Table 2 lists the catalytic performance of 1%Ni/SBA-15(P) and recently reported RWGS catalysts, and the 1%Ni/SBA-15(P) catalyst exhibits excellent RWGS catalytic performance.

In summary, the 1%Ni/SBA-15(P) was active and stable during the RWGS at high-temperature. The characteristic results proved that the NiO particles were highly dispersed.
and confined in mesoporous SiO\(_2\) channels for the 1\%Ni/SBA-15(P) catalyst, and the nickel strongly interacted with SiO\(_2\) support. Based on the characterization and catalytic test results, the good activity and stability of the 1\%Ni/SBA-15(P) catalyst was due to the small Ni particle and enhanced interaction between Ni and SiO\(_2\).

4. Conclusions
A highly dispersed 1\%Ni/SBA-15(P) catalyst, with Ni particle size at about 3 nm, was synthesized, which was highly active and stable during the high-temperature RWGS reaction. Based on the characterizations, it was proposed that the excellent catalytic performance was due to the small Ni particles and the metal-support interaction.

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References
1. Nedolivko, V.V.; Zasypalov, G.O.; Vutolkina, A.V.; Gushchin, P.A.; Vinokurov, V.A.; Kulikov, L.A.; Egazar’yants, S.V.; Karakhanov, E.A.; Maksimov, A.L.; Glotov, A.P. Carbon Dioxide Reforming of Methane. Russ. J. Appl. Chem. 2020, 93, 765–787. [CrossRef]
2. Li, Z.; Das, S.; Hongmanorom, P.; Dewangan, N.; Wai, M.H.; Kawi, S. Silica-based micro- and mesoporous catalysts for dry reforming of methane. Catal. Sci. Technol. 2018, 8, 2763–2778. [CrossRef]
3. Chotirach, M.; Tantayanon, S.; Tungasmita, D.N.; Sun, J.; Tungasmita, S. Synthesis and characterizations of TiN–SBA-15 mesoporous materials for CO\(_2\) dry reforming enhancement. Pure Appl. Chem. 2020, 92, 545–556. [CrossRef]
4. Zhu, M.; Ge, Q.; Zhu, X. Catalytic Reduction of CO\(_2\) to CO via Reverse Water Gas Shift Reaction: Recent Advances in the Design of Active and Selective Supported Metal Catalysts. Trans. Tianjin Univ. 2020, 26, 172–187. [CrossRef]
5. Daza, Y.A.; Kuhn, J.N. CO\(_2\) conversion by reverse water gas shift catalysis: Comparison of catalysts, mechanisms and their consequences for CO\(_2\) conversion to liquid fuels. RSC Adv. 2016, 6, 49675–49691. [CrossRef]
6. Gonzalez-Castaño, M.; Dorneanu, B.; Arellano-Garcia, H. The reverse water gas shift reaction: A process systems engineering perspective. React. Chem. Eng. 2021, 6, 954–976. [CrossRef]
7. Gorbunov, D.N.; Semerina, V.A.; Terenina, M.V.; Kardasheva, Y.S.; Maksimov, A.L.; Karakhanov, E.A. Catalytic Decomposition of Methyl Formate in the Presence of Transition Metal Complexes, Phosphine Ligands and Water. Pet. Chem. 2019, 59, 412–419. [CrossRef]
8. Gorbunov, D.N.; Nenasheva, M.V.; Kardasheva, Y.S.; Karakhanov, E.A. Alternative sources of syngas for hydroformylation of unsaturated compounds. Russ. Chem. Bull. 2020, 69, 625–634. [CrossRef]
9. Wang, L.; Zhang, S.; Liu, Y. Reverse water gas shift reaction over Co-precipitated Ni-Ce\(_2\)O\(_2\) catalysts. J. Rare Earths 2008, 26, 66–70. [CrossRef]
10. Zonetti, P.C.; Letichevsky, S.; Gaspar, A.B.; Sousa-Aguiar, E.F.; Appel, L.G. The Ni\(_{x}\)Ce\(_{0.75}\)Zr\(_{0.25}\)O\(_2\)–SiO\(_2\) solid solution and the RWGS. Appl. Catal. A: Gen. 2014, 474, 48–54. [CrossRef]
11. Sun, F.-m.; Yan, C.-f.; Wang, Z.-d.; Guo, C.-q.; Huang, S.-l. Ni/Co–Ce–Zr–O catalyst for high CO\(_2\) conversion during reverse water gas shift reaction (RWGS). Int. J. Hydrogen Energy 2015, 40, 15985–15993. [CrossRef]
12. Gonçalves, R.V.; Vono, L.L.R.; Wojcieszak, R.; Dias, C.S.B.; Wender, H.; Teixeira-Neto, E.; Rossi, L.M. Selective hydrogenation of CO\(_2\) into CO on a highly dispersed nickel catalyst obtained by magnetron sputtering deposition: A step towards liquid fuels. Appl. Catal. B Environ. 2017, 209, 240–246. [CrossRef]
13. Nie, W.; Zou, X.; Chen, C.; Wang, X.; Ding, W.; Lu, X. Methanation of Carbon Dioxide over Ni–Ce–Zr Oxides Prepared by One-Pot Hydrolysis of Metal Nitrates with Ammonium Carbonate. Catalysts 2017, 7, 104. [CrossRef]
14. Wu, H.C.; Chang, Y.C.; Wu, J.H.; Lin, J.H.; Lin, I.K.; Chen, C.S. Methanation of CO\(_2\) and reverse water gas shift reactions on Ni/SiO\(_2\) catalysts: The influence of particle size on selectivity and reaction pathway. Catal. Sci. Technol. 2015, 5, 4154–4163. [CrossRef]
15. Vutolkina, A.V.; Glotov, A.P.; Zanina, A.V.; Makhmutov, D.F.; Maximov, A.L.; Egazar’yants, S.V.; Karakhanov, E.A. Mesoporous Al-HMS and Al-MCM-41 supported Ni-Mo sulfide catalysts for HYD and HDS via in situ hydrogen generation through a WGSR. *Catal. Today* 2019, 329, 156–166. [CrossRef]

16. Carta, D.; Montini, T.; Casula, M.F.; Monai, M.; Bullita, S.; Fornasiero, P.; Corrias, A. The water gas shift reaction over Pt–CeO2 nanoparticles confined within mesoporous SBA-16. *J. Mater. Chem. A* 2017, 5, 20024–20034. [CrossRef]

17. Singh, S.; Kumar, R.; Setiabudi, H.D.; Nanda, S.; Vo, D.-V.N. Advanced synthesis strategies of mesoporous SBA-15 supported catalysts for catalytic reforming applications: A state-of-the-art review. *Appl. Catal. A Gen.* 2018, 559, 57–74. [CrossRef]

18. Xin, Q.; Glisenti, A.; Philippopoulos, C.; Poullakis, E.; Mertens, M.; Nyalosaso, J.; Meynen, V.; Cool, P. Comparison between a Water-Based and a Solvent-Based Impregnation Method towards Dispersed CuO/SBA-15 Catalysts: Texture, Structure and Catalytic Performance in Automotive Exhaust Gas Abatement. *Catalysts* 2016, 6, 164. [CrossRef]

19. Ortega-Domínguez, R.A.; Vargas-Villagrán, H.; Peñaloza-Orta, C.; Saavedra-Rubio, K.; Bokhimi, X.; Klímova, T.E. A facile method to increase metal dispersion and hydrogenation activity of Ni/SBA-15 catalysts. *Fuel* 2017, 198, 110–122. [CrossRef]

20. Wu, H.; Liu, H.; Yang, W.; He, D. Synergetic effect of Ni and Co in Ni–Co/SBA-15-CD catalysts and their catalytic performance in carbon dioxide reforming of methane to syngas. *Catal. Sci. Technol.* 2016, 6, 5631–5646. [CrossRef]

21. Tao, M.; Xin, Z.; Meng, X.; Bian, Z.; Lv, Y. Highly dispersed nickel within mesochannels of SBA-15 for CO methanation with enhanced activity and excellent thermostability. *Fuel* 2017, 188, 267–276. [CrossRef]

22. Lu, B.; Ju, Y.; Abe, T.; Kawamoto, K. Grafting Ni particles onto SBA-15, and their enhanced performance for CO methanation. *RSC Adv.* 2015, 5, 56444–56454. [CrossRef]

23. Liu, H.; Li, Y.; Wu, H.; Miyake, T.; He, D. CO2 reforming of methane over Ni/SBA-15 prepared with β-cyclodextrin—Role of β-cyclodextrin in Ni dispersion and performance. *Chem. Eng. J.* 2016, 302, 88–97. [CrossRef]

24. Li, D.; Zeng, L.; Li, X.; Wang, X.; Ma, H.; Assabumrungrat, S.; Gong, J. Ceria-promoted Ni/SBA-15 catalysts for ethanol steam reforming with enhanced activity and resistance to deactivation. *Appl. Catal. B Environ.* 2015, 161, 352–341. [CrossRef]

25. Carrero, A.; Calles, J.A.; Garcia-Moreno, L.; Vizcaíno, A.J. Production of Renewable Hydrogen from Glycerol Steam Reforming over Bimetallic Ni-(Cu, Co, Cr) Catalysts Supported on SBA-15 Silica. *Catalysts* 2017, 7, 55. [CrossRef]

26. Lu, B.; Kawamoto, K. Preparation of monodispersed NiO nanoparticles in SBA-15, and its enhanced selectivity for reverse water gas shift reaction. *J. Environ. Eng. Chem.* 2013, 1, 300–309. [CrossRef]

27. Zhao, D.; Feng, J.; Huo, Q.; Melosh, N.; Fredrickson, G.H.; Chmelka, B.F.; Stucky, G.D. Triblock Copolymer Syntheses of Mesoporous Silica with Periodic 50 to 300 Angstrom Pores. *Science* 1998, 279, 548–552. [CrossRef]

28. Yang, W.; Liu, H.; Li, Y.; Wu, H.; He, D. CO2 reforming of methane to syngas over highly-stable Ni/SBA-15 catalysts prepared by P123-assisted method. *Int. J. Hydrogen Energy* 2016, 41, 1513–1523. [CrossRef]

29. Yang, W.; Liu, H.; Li, Y.; He, D. Interaction mechanism of Ni(NO3)2·6H2O and P123 in preparing highly-dispersed Ni/SBA-15 catalytic materials. *Microporous Mesoporous Mater.* 2016, 228, 174–181. [CrossRef]

30. Kruk, M.; Jaronec, M.; Ko, C.H.; Ryoo, R. Characterization of the Porous Structure of SBA-15. *Chem. Mater.* 2000, 12, 1961–1968. [CrossRef]

31. Tao, M.; Xin, Z.; Meng, X.; Lv, Y.; Bian, Z. Impact of double-solvent impregnation on the Ni dispersion of Ni/SBA-15 catalysts and catalytic performance for the syngas methanation reaction. *RSC Adv.* 2016, 6, 53875–53883. [CrossRef]

32. Liu, Z.; Zhou, J.; Cao, K.; Yang, W.; Gao, H.; Wang, Y.; Li, H. Highly dispersed nickel loaded on mesoporous silica: One-spot synthesis strategy and high performance as catalysts for methane reforming with carbon dioxide. *Appl. Catal. B Environ.* 2012, 125, 324–330. [CrossRef]

33. He, S.; He, S.; Zhang, L.; Li, X.; Wang, J.; He, D.; Lu, J.; Luo, Y. Hydrogen production by ethanol steam reforming over Ni/SBA-15 mesoporous catalysts: Effect of Au addition. *Catal. Today* 2015, 258 Pt 1, 162–168. [CrossRef]

34. Zhang, Q.; Zhang, T.; Shi, Y.; Zhao, B.; Wang, M.; Liu, Q.; Wang, J.; Long, K.; Duan, Y.; Ning, P. A sintering and carbon-resistant Ni-SBA-15 catalyst prepared by solid-state grinding method for dry reforming of methane. *J. CO2 Util.* 2017, 17, 10–19. [CrossRef]

35. Zhang, Q.; Long, K.; Wang, J.; Zhang, T.; Song, Z.; Lin, Q. A novel promoting effect of chelating ligand on the dispersion of Ni species over Ni/SBA-15 catalyst for dry reforming of methane. *Int. J. Hydrogen Energy* 2017, 42, 14103–14114. [CrossRef]

36. Wang, M.; Zhang, Q.; Zhang, T.; Wang, Y.; Wang, J.; Long, K.; Song, Z.; Liu, X.; Ning, P. Facile one-pot synthesis of highly dispersed Ni nanoparticles embedded in HMS for dry reforming of methane. *Chem. Eng. J.* 2017, 313, 1370–1381. [CrossRef]

37. Tao, M.; Meng, X.; Lv, Y.; Bian, Z.; Xin, Z. Effect of impregnation solvent on Ni dispersion and catalytic properties of Ni/SBA-15 for CO methanation reaction. *Fuel* 2016, 165, 289–297. [CrossRef]

38. Wang, J.; Du, C.; Wei, Q.; Shen, W. Two-Dimensional Pd Nanosheets with Enhanced Catalytic Activity for Selective Hydrogenation of Nitrobenzene to Aniline. *Energy Fuels* 2021, 35, 4358–4366. [CrossRef]

39. Zhang, X.; Zhu, X.; Lin, L.; Yao, S.; Zhang, M.; Liu, X.; Wang, Y.; Li, Y-W.; Shi, C.; Ma, D. Highly Dispersed Copper over β-Mo2C as an Efficient and Stable Catalyst for the Reverse Water Gas Shift (RWGS) Reaction. *ACS Catal.* 2017, 7, 912–918. [CrossRef]

40. Liang, B.; Duan, H.; Su, X.; Chen, X.; Huang, Y.; Chen, X.; Delgado, J.J.; Zhang, T. Promoting role of potassium in the reverse water gas shift reaction on Pt/mullite catalyst. *Catal. Today* 2017, 281, 319–326. [CrossRef]