



Methane combustion over Pd/ZrO₂/SiC, Pd/CeO₂/SiC, and Pd/Zr_{0.5}Ce_{0.5}O₂/SiC catalysts

Xiaoning Guo, Guojuan Zhi, Xiaoyan Yan, Guoqiang Jin, Xiangyun Guo, Pascal Brault

► To cite this version:

Xiaoning Guo, Guojuan Zhi, Xiaoyan Yan, Guoqiang Jin, Xiangyun Guo, et al.. Methane combustion over Pd/ZrO₂/SiC, Pd/CeO₂/SiC, and Pd/Zr_{0.5}Ce_{0.5}O₂/SiC catalysts. *Catalysis Communications*, 2011, 12, pp.870-874. hal-00579764

HAL Id: hal-00579764

<https://hal.science/hal-00579764>

Submitted on 31 Mar 2011

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Methane Combustion over Pd/ZrO₂/SiC, Pd/CeO₂/SiC, Pd/Zr_{0.5}Ce_{0.5}O₂/SiC Catalysts

Xiaoning Guo ^{a,c}, Guojuan Zhi ^{a,c}, Xiaoyan Yan ^{a,c}, Guoqiang Jin ^a,
Xiangyun Guo ^{a,*}, Pascal Brault ^{b,*}

^a State Key Laboratory of Coal Conversion, Institute of Coal Chemistry, Taiyuan 030001, PR China

^b GREMI UMR6606 CNRS - Université d'Orléans BP6744, 45067 ORLEANS Cedex2, France

^c Graduate University of the Chinese Academy of Sciences, Beijing 100039, PR China

Abstract

The performances of different promoters (CeO₂, ZrO₂ and Ce_{0.5}Zr_{0.5}O₂ solid solution) modified Pd/SiC catalysts for methane combustion are studied. XRD and XPS results showed that Zr⁴⁺ could be incorporated into the CeO₂ lattice to form Zr_{0.5}Ce_{0.5}O₂ solid solution. The catalytic activities of Pd/CeO₂/SiC and Pd/ZrO₂/SiC are lower than that of Pd/Zr_{0.5}Ce_{0.5}O₂/SiC. The Pd/Zr_{0.5}Ce_{0.5}O₂/SiC catalyst can ignite the reaction at 240°C and obtain a methane conversion of 100% at 340°C, and keep 100 % methane conversion after 10 reaction cycles. These results indicate that active metallic nanoparticles are well stabilized on the SiC surface while the promoters serve as oxygen reservoir and retain good redox properties.

Keywords: High surface area SiC; Pd/SiC catalysts; Zr_{0.5}Ce_{0.5}O₂ solid solution; methane combustion.

*Corresponding authors:

Fax: +86-351 4050320; Tel: +86-351 4065282

Email: xyguo@sxicc.ac.cn (X. Y. Guo)

Fax: +33- 2 38 41 71 54; Tel: +33- 2 38 41 71 25

Email: Pascal.Brault@univ-orleans.fr (P. Brault)

1. Introduction

Supported palladium catalysts have been found to have excellent activity toward the catalytic combustion of methane, which has been found to be more environmentally friendly than traditional flame combustion due to lower emissions of NO_x , CO, and unburned hydrocarbons^[1,2]. Usually, the supports of Pd-based catalysts are thermal insulators, such as SiO_2 and Al_2O_3 . The methane combustion is a strongly exothermic reaction, therefore the reaction heat accumulated on isolated metal nanoparticles makes them easily sintered^[3-5]. It has been established that SiC can be a potentially excellent catalyst support for various reactions since SiC has admirable chemical stability and high thermal conductivity and stability^[6-8]. Our previous study showed that Pd/SiC catalyst using etched SiC nanowires as the support can completely convert CH_4 at about 390°C and run 10 reaction cycles without any decrease in the catalytic activity^[9].

It is well known that CeO_2 and ZrO_2 are effective promoters for noble-based combustion catalysts because they can enhance the dispersion and stability of metallic active phases. However CeO_2 is easily sintered at high reaction temperatures, and ZrO_2 has the drawbacks of high cost and relatively low surface area^[10-13]. Therefore, researchers have suggested that formation of a $\text{Ce}_{0.5}\text{Zr}_{0.5}\text{O}_2$ solid solution by adding ZrO_2 to CeO_2 can improve oxygen storage capacity, redox properties, thermal resistance and catalytic activity of catalysts at lower temperatures^[14-17]. In this work, we investigate Pd/SiC catalysts modified by CeO_2 , ZrO_2 and $\text{Zr}_{0.5}\text{Ce}_{0.5}\text{O}_2$ solid solution respectively, which show excellent activity and stability for methane combustion.

2. Experiments

2.1 Catalyst Preparation

The catalysts are 1wt.% Pd supported on either SiC ($S_{\text{BET}}=50.8\text{m}^2/\text{g}$)^[18, 19] or SiC modified with 1% promoters (ZrO_2 , CeO_2 and $\text{Zr}_{0.5}\text{Ce}_{0.5}\text{O}_2$) and were prepared by the impregnation method. First,

0.4g SiC was added into 20ml aqueous solution of $\text{Zr}(\text{NO}_3)_4 \cdot 5\text{H}_2\text{O}$ (0.05wt.%), $\text{Ce}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$ (0.05wt.%) separately and into the above two nitrate mixture (Zr: 0.025wt.%; Ce: 0.025wt.%) under stirring for 12 hours. Afterwards all the mixtures were dried at 110°C for 12 hours and then calcined in air at 500°C for 4 hours. Then, 0.4g of SiC and the modified supports were separately added into 20ml $\text{Pd}(\text{NO}_3)_2 \cdot 2\text{H}_2\text{O}$ aqueous solution (0.05wt.%); and we repeat the above method to prepare different 1wt.% Pd-based catalysts. The catalysts were marked as Pd/SiC, Pd/ ZrO_2 /SiC, Pd/ CeO_2 /SiC and Pd/ $\text{Zr}_{0.5}\text{Ce}_{0.5}\text{O}_2$ /SiC, respectively. For comparison, 1wt.% Pd/ Al_2O_3 catalyst was also prepared by impregnating $\gamma\text{-Al}_2\text{O}_3$ ($S_{\text{BET}}=160\text{m}^2/\text{g}$) with $\text{Pd}(\text{NO}_3)_2 \cdot 2\text{H}_2\text{O}$ aqueous solution.

2.2 Catalytic test

The catalytic performance of the different catalysts for the methane combustion was carried out in a fixed-bed quartz reactor with an inner diameter of 8 mm at atmospheric pressure, and the mixture of O_2 (20 %)/ CH_4 (1 %)/ N_2 (79 %) was used as the feedstock. 300 mg of the catalyst was packed between two layers of quartz wool. The hourly space velocity was controlled to be 10000h^{-1} . Since the deactivation of the SiC-supported catalysts usually demands a long time, a repeated heating-then-cooling cycle method was employed to estimate the stabilities of the catalysts as previously reported^[9].

2.3 Catalyst characterization

The crystalline phases of different catalysts were characterized by a Rigaku D-Max/RB X-ray diffractometer (XRD) with Cu $K\alpha$ radiation. The microstructures of the catalysts were analyzed by using a JEOL-2010 transmission electron microscope (TEM) and JEM-2010 high-resolution transmission electron microscope (HRTEM). X-ray photoelectron spectroscopy (XPS) were carried out on a Kratos XSAM800 spectrometer by using Al $K\alpha$ ($h\nu = 1486.6\text{ eV}$) X-ray source.

3. Results and discussion

3.1 XRD and XPS characterization of fresh catalysts

From the XRD patterns of different fresh catalysts shown in Fig.1, the strong diffraction peak ($2\theta=35.8^\circ$) can be indexed to β -SiC. All the catalysts present an obvious peak at $2\theta=33.8^\circ$, which attributed to the tetragonal PdO. Pd/ZrO₂/SiC presents two peaks at near 28.1° and 31.4° (2θ), assigned to monoclinic ZrO₂. The main peaks at 28.8° and 33.3° (2θ) in the XRD patterns of Pd/CeO₂/SiC correspond to the cubic, fluorite structures of CeO₂. The diffraction peaks ascribed to ZrO₂ were not observed in Pd/Zr_{0.5}Ce_{0.5}O₂/SiC. However the 2θ -values of CeO₂ peaks increase from 28.8° and 33.3° to 29.1° and 33.5° , respectively. This is due to Zr⁴⁺ has incorporated into the CeO₂ lattice, and caused the change of CeO₂ crystal phase and the formation of Zr_{0.5}Ce_{0.5}O₂ solid solution^[20,21].

Fig.2 represents the XPS spectra of fresh Pd/ZrO₂/SiC, Pd/CeO₂/SiC and Pd/Zr_{0.5}Ce_{0.5}O₂/SiC. The peak at 337.6 - 337.7 eV shown in Fig.2a corresponds to the Pd 3d_{5/2}. Generally, there are three components with Pd 3d_{5/2} bonding energy (BE) values in 334.7-335.1 eV, 337.6-337.8 eV and 338.4-338.5 eV, which are usually attributed to Pd⁰, Pd²⁺ and Pd⁴⁺, respectively^[22-24]. Therefore, the valence of Pd atoms in these three catalysts is +2. The peaks of Pd/ZrO₂/SiC at about 181.4 and 183.7 eV shown in Fig.2b correspond to the Zr 3d_{5/2} and Zr 3d_{3/2}, respectively. The difference in the binding energies between the Zr 3d_{5/2} and Zr 3d_{3/2} photoemission feature is 2.3 eV, which is in agreement with the reported value^[25]. Nelson and Schulz reported that the band located at 900.2-900.6 eV was the Ce 3d_{3/2} ionization and the band located at 881.7-882.0 eV was the Ce 3d_{5/2} ionization^[25]. Therefore, the peaks of Pd/CeO₂/SiC at about 900.2 and 881.7 eV shown in Fig. 2c should be the principal binding energies of Ce 3d_{3/2} and Ce 3d_{5/2}, respectively. The

peaks at about 897.6 and 916.1 eV are satellites arising from the Ce 3d_{3/2} and Ce 3d_{5/2}. According to the literature, in the Ce-Zr mixed oxide with 15-80% of Ce the peak position of Zr 3d_{5/2} usually occurs at 181.7-181.8 eV and the Ce 3d_{5/2} peak at 881.8-882.1 eV^[26]. In the case of our study, the peak of Pd/Zr_{0.5}Ce_{0.5}O₂/SiC at about 181.7 eV (Fig.2b) corresponds to the Zr 3d_{5/2}, while the peak of Pd/Zr_{0.5}Ce_{0.5}O₂/SiC at about 882.1 eV (Fig.2c) corresponds to the Ce 3d_{5/2}. Thus, the majority of ZrO₂ and CeO₂ of Pd/Zr_{0.5}Ce_{0.5}O₂/SiC are in the form of Ce_{0.5}Zr_{0.5}O₂ solid solution but not in the form of separate ZrO₂ and CeO₂. From Fig.2c, the peak of Pd/Zr_{0.5}Ce_{0.5}O₂/SiC at about 900.8 eV is the principal binding energies of Ce 3d_{3/2}, and the peaks at about 897.8 eV and 916.3 eV are satellites arising from the Ce 3d_{3/2} and Ce 3d_{5/2}.

3.2 TEM and HRTEM characterization

Fig.3 shows TEM images of fresh and used Pd/SiC catalysts. From Fig.3a, the lattice spacings of nanoparticle are 0.262 nm and 0.269 nm, which are indexed as the (101) and (002) planes of tetragonal PdO. The PdO nanoparticles in Pd/SiC have a narrow size distribution from 2 to 4 nm and an average diameter of 2.6 nm according to our statistical analysis (Fig.3a). From Fig.3b, the lattice spacing of nanoparticles is 0.263 nm, which corresponds to (101) planes of tetragonal PdO, claiming the active phase PdO has not been decomposed into metallic Pd during the cyclic reaction. The average size of PdO particles only has a slight increase from 2.6 to 2.8 nm after the cyclic reaction (Fig.3b). The above results suggest that PdO nanoparticles are very stable on the surface of SiC because of the high thermal conductivity and chemical stability of the high surface area SiC, which can effectively hinder the sintering of active nanoparticles and thus stabilize them.

Fig.4 shows TEM images of fresh Pd/SiC catalysts modified by ZrO₂, CeO₂ and Zr_{0.5}Ce_{0.5}O₂. PdO nanoparticles could not be found in Fig.4 possibly because they are too small to be found out.

The lattice spacing of nanoparticles is 0.205 nm, which is attributed to the interplanar spacing of (211) plane of monoclinic ZrO_2 (Fig.4a). The lattice spacings of 0.311, 0.312, 0.315 and 0.276 nm are indexed as the (111) and (200) of cubic CeO_2 (Fig.4b). The lattice spacing of 0.291 nm corresponds to the (111) planes of cubic $\text{Zr}_{0.5}\text{Ce}_{0.5}\text{O}_2$. Compared with pure CeO_2 , the interplanar spacing has a little decrease, suggesting that Zr^{4+} has inserted into the CeO_2 crystal lattice, which may cause the change of CeO_2 crystal phase^[21].

3.3 Catalytic performances

Fig.5 shows the results of activities and stabilities of different catalysts. From Fig.5a, $T_{10\%}$ (temperature of 10% methane conversion) and $T_{100\%}$ (temperature of methane complete conversion) of Pd/SiC is 285°C and 370°C respectively, which are nearly equal to those of $\text{Pd}/\text{Al}_2\text{O}_3$ catalyst. ZrO_2 modification can reduce $T_{10\%}$ from 285°C to 230°C and $T_{100\%}$ from 370°C to 350°C because ZrO_2 excellent low temperature activity, oxygen storage capacity and transfer ability. CeO_2 modification can reduce $T_{10\%}$ from 285°C to 245°C and $T_{100\%}$ from 370°C to 360°C , separately. CeO_2 could increase the oxidizability of crystal boundary and form a synergistic effect between the active phases and supports, therefore improve the catalytic activity and stability^[12,13]. Nevertheless, $\text{Zr}_{0.5}\text{Ce}_{0.5}\text{O}_2$ solid solution modification can significantly reduce $T_{10\%}$ from 285°C to 240°C and $T_{100\%}$ from 370°C to 340°C respectively, suggesting that $\text{Zr}_{0.5}\text{Ce}_{0.5}\text{O}_2$ solid solution could strongly improve oxygen storage capacity and thermal resistance^[14-17]. This also means that the combustion reaction could be finished in a narrow temperature range (around 100°C).

Fig.5b shows the results of stability of $\text{Pd}/\text{Al}_2\text{O}_3$. The final methane conversion left only 67.4% at 370°C after 10 reaction cycles mainly because of the sintering of γ -alumina and coalescence of PdO nanoparticles^[4, 5, 27]. However, the Pd/SiC (Fig.5c) and $\text{Pd}/\text{Zr}_{0.5}\text{Ce}_{0.5}\text{O}_2/\text{SiC}$ (Fig.5d) catalysts

can keep the methane conversion at almost 100 % after 10 reaction cycles, indicating that high surface area SiC supported catalysts have excellent stability in methane combustion. This further confirms the previous results from TEM images of catalysts that high surface area SiC can significantly hinder the migration and coalescence of active phase nanoparticles and thus stabilize them.

4. Conclusion

Pd-based catalysts using high surface area SiC ($50.8\text{m}^2/\text{g}$) modified by CeO_2 , ZrO_2 and $\text{Ce}_{0.5}\text{Zr}_{0.5}\text{O}_2$ solid solution as the support could effectively increase the dispersion and activity of active metallic phases. XRD and XPS studies showed that Zr^{4+} could be incorporated into the CeO_2 lattice to form $\text{Zr}_{0.5}\text{Ce}_{0.5}\text{O}_2$ solid solution. $T_{10\%}$ and $T_{100\%}$ of $\text{Pd}/\text{Zr}_{0.5}\text{Ce}_{0.5}\text{O}_2/\text{SiC}$ are 240°C and 340°C respectively and the reaction could be finished in a narrow temperature range (around 100°C) certainly due to the excellent oxygen storage capacity, redox properties, thermal stability and low temperature catalytic activity of $\text{Ce}_{0.5}\text{Zr}_{0.5}\text{O}_2$ solid solution. However, $\text{Pd}/\text{CeO}_2/\text{SiC}$ and $\text{Pd}/\text{ZrO}_2/\text{SiC}$ have lower catalytic activity than $\text{Pd}/\text{Zr}_{0.5}\text{Ce}_{0.5}\text{O}_2/\text{SiC}$. All the SiC-based catalysts can keep the methane conversion of almost 100 % after 10 reaction cycles suggesting that active nanoparticles are well stabilized on the SiC surface while the promoters serve as oxygen reservoir and retain good redox properties.

Acknowledgment

The work was financially supported by Shanxi Province (Ref: 2008011014-1), NSFC (20973190) and MOST (Ref: SKLCC-2008BWZ010 and 2011CB201405).

References

[1] D. Ciuparu, M. R. Lyubovsky, E. Altman, L. D. Pfefferle, A. Datye, Catal. Rev. 44 (2002) 593.

- [2] P. G  lin, M. Primet, Appl. Catal. B 39 (2002) 1.
- [3] R. J. Farrauto, J. K. Lampert, M. C. Hobson, E. M. Waterman, Appl. Catal. B 6 (1995) 263.
- [4] F. X. Yin, S. F. Ji, P. Y. Wu, F. Z. Zhao, C. Y. Li, J. Catal. 257 (2008) 108.
- [5] Y. Ozawa, Y. Tochihara, A. Watanabe, M. Nagai, S. Omi, Appl. Catal. A 259 (2004) 1.
- [6] R. J. Shang, Y. Y. Wang, G. Q. Jin, X. Y. Guo, Catal. Commun. 10 (2009) 1502.
- [7] S. Ivanova, E. Vanhaecke, L. Dreibine, B. Louis, C. Pham, C. Pham-Huu, Appl. Catal. A 359 (2009) 151.
- [8] A. Berthet, A. L. Thomann, F. J. Cadete Santos Aires, M. Brun, C. Deranlot, J. C. Bertolini, J. P. Rozenbaum, P. Brault, P. Andreazza, J. Catal. 190 (2000) 49.
- [9] X. N. Guo, R. J. Shang, D. H. Wang, G. Q. Jin, X. Y. Guo, K. N. Tu, Nanoscale Res. Lett. 5 (2010) 332.
- [10] J. Krishna Murthy, S. Chandra Shekar, V. Siva Kumar, K. S. Rama Rao, Catal. Commun. 3 (2002) 145.
- [11] C. A. M  ller, M. Maciejewski, R. A. Koepfel, A. Baiker, Catal. Today 47 (1999) 245.
- [12] S. Colussi, A. Trovarelli, G. Groppi, J. Llorca, Catal. Commun. 8 (2007) 1263.
- [13] P. O. Thevenin, A. Alcalde, L. J. Pettersson, S. G. J  r  s, J. L. G. Fierro, J. Catal. 215 (2003) 78.
- [14] R. Di Monte, P. Fornasiero, J. Ka  par, P. Rumori, G. Gubitosa, M. Graziani, Appl. Catal. B 24 (2000) 157.
- [15] M. Haneda, O. Houshito, T. Sato, H. Takagi, K. Shinoda, Y. Nakahara, K. Hiroe, H. Hamada, Catal. Commun. 11 (2010) 317.
- [16] P. Fornasiero, R. Di Monte, G. Rsga Rao, J. Kaspar, S. Meriani, A. Trovarelli, M. Graziani, J.

Catal. 151 (1995) 168.

[17] G. Balducci, P. Fornasiero, R. Di Monte, J. Kaspar, S. Meriani, M. Graziani, Catal. Lett. 33 (1995) 193.

[18] G. Q. Jin, X. Y. Guo, Micropor. Mesopor. Mat. 60 (2003) 207.

[19] X. Y. Guo, G. Q. Jin, J. Mater. Sci. 40 (2005) 1301.

[20] S. P. Wang, X. C. Zheng, X. Y. Wang, S. R. Wang, S. M. Zhang, L. H. Yu, W. P. Huang, S. H. Wu, Catal. Lett. 105 (2005) 163.

[21] G. Vlaic, R. Di Monte, P. Fornasiero, E. Fonda, J. Kašpar, M. Graziani, J. Catal. 182 (1999) 378.

[22] N. Ikeo, Y. Iijima, N. Nimura, M. Sigematsu, T. Tazawa, S. Matsumoto, K. Kojima, Y. Nagasawa, Handbook of X-Ray Photoelectron Spectroscopy, JEOL, Tokyo, 1991.

[23] L. M. T. Simplicio, S. T. Brandão, E. A. Sales, L. Lietti, F. Bozon-Verduraz, Appl. Catal. B 63 (2006) 9.

[24] K. Otto, L. P. Haack, J. E. deVries, Appl. Catal. B 1 (1992) 1.

[25] A. E. Nelson, K. H. Schulz, Appl. Surf. Sci. 210 (2003) 206.

[26] A. Galtayries, R. Sporken, J. Riga, G. Blanchard, R. Caudano, J. Electron Spectrosc. Rel. Phen. 88 (1998) 951.

[27] H. Arai, M. Machida, Catal. Today 10 (1991) 81.

Figures captions:

Fig. 1 XRD patterns of different catalysts.

Fig. 2 XPS patterns of Pd/ZrO₂/SiC, Pd/CeO₂/SiC and Pd/Zr_{0.5}Ce_{0.5}O₂/SiC: (a) Pd 3d, (b) Zr 3d and (c) Ce 3d.

Fig. 3 TEM images of fresh (a) and used (b) Pd/SiC, and the inserted figures are the HRTEM of different catalysts themselves.

Fig. 4 TEM images of different fresh modified catalysts: Pd/ZrO₂/SiC (a), Pd/CeO₂/SiC (b) and Pd/Zr_{0.5}Ce_{0.5}O₂/SiC (c); and the inserted figures are HRTEM of different catalysts themselves.

Fig. 5 Catalytic performances of different catalysts for methane combustion: the activities of different catalysts (a); and cyclic reaction results of Pd/Al₂O₃ (b), Pd/SiC (c) and Pd/Zr_{0.5}Ce_{0.5}O₂/SiC (d).

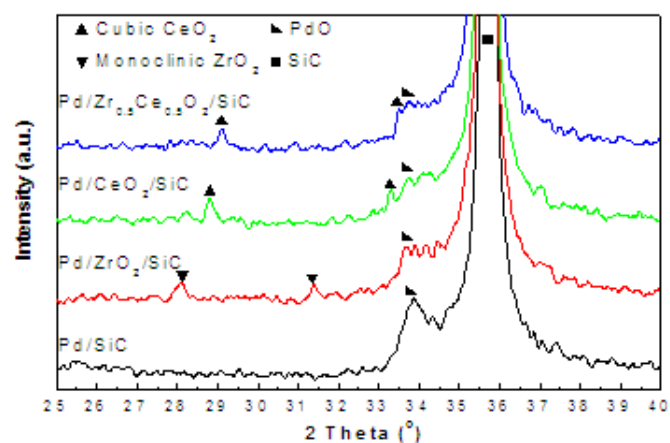


Fig. 1 XRD patterns of different catalysts.

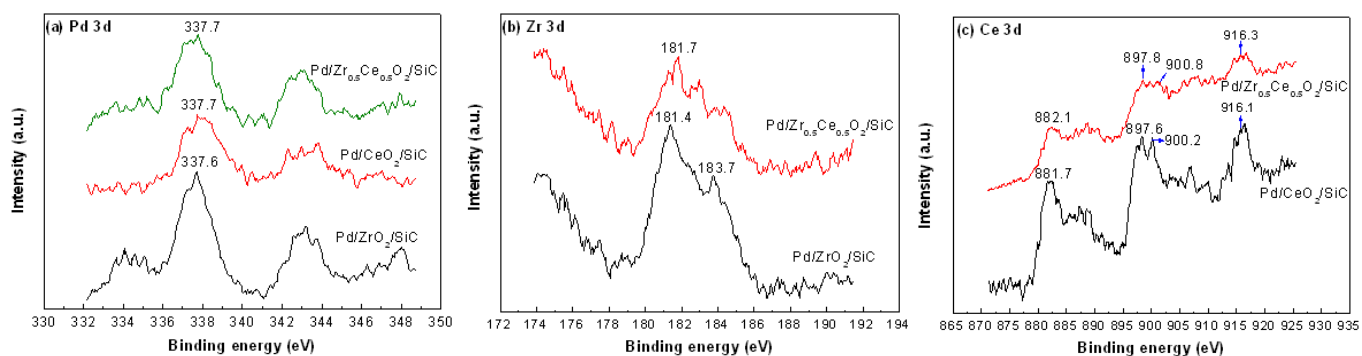


Fig. 2 XPS patterns of Pd/ZrO₂/SiC, Pd/CeO₂/SiC and Pd/Zr_{0.5}Ce_{0.5}O₂/SiC: (a) Pd 3d, (b) Zr 3d and (c) Ce 3d.

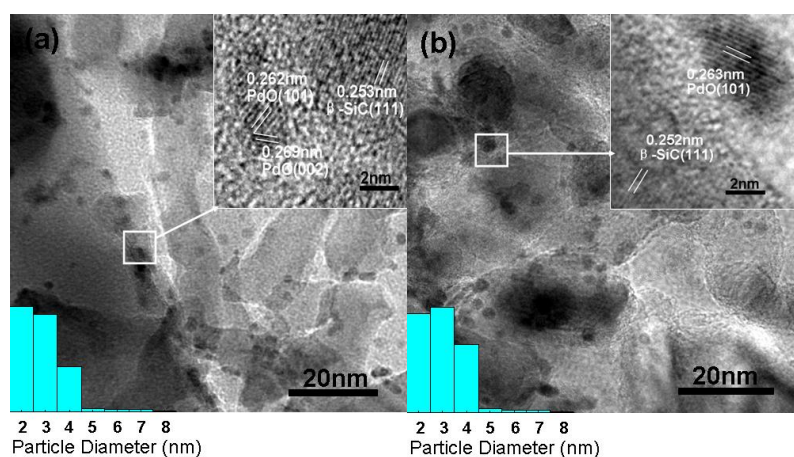


Fig. 3 TEM images of fresh (a) and used (b) Pd/SiC, and the inserted figures are the HRTEM of different catalysts themselves.

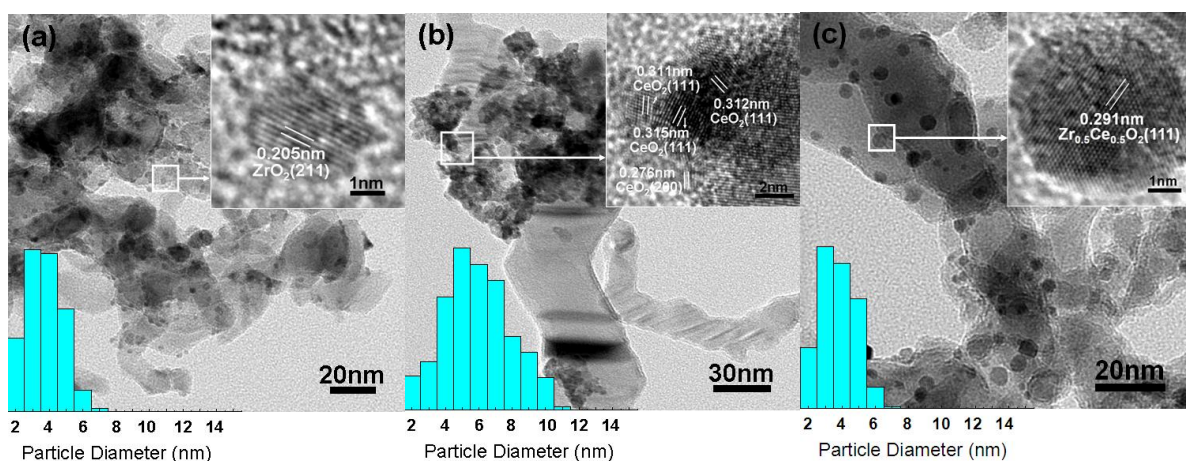


Fig. 4 TEM images of different fresh modified catalysts: Pd/ZrO₂/SiC (a), Pd/CeO₂/SiC (b) and Pd/Zr_{0.5}Ce_{0.5}O₂/SiC (c); and the inserted figures are HRTEM of different catalysts themselves.

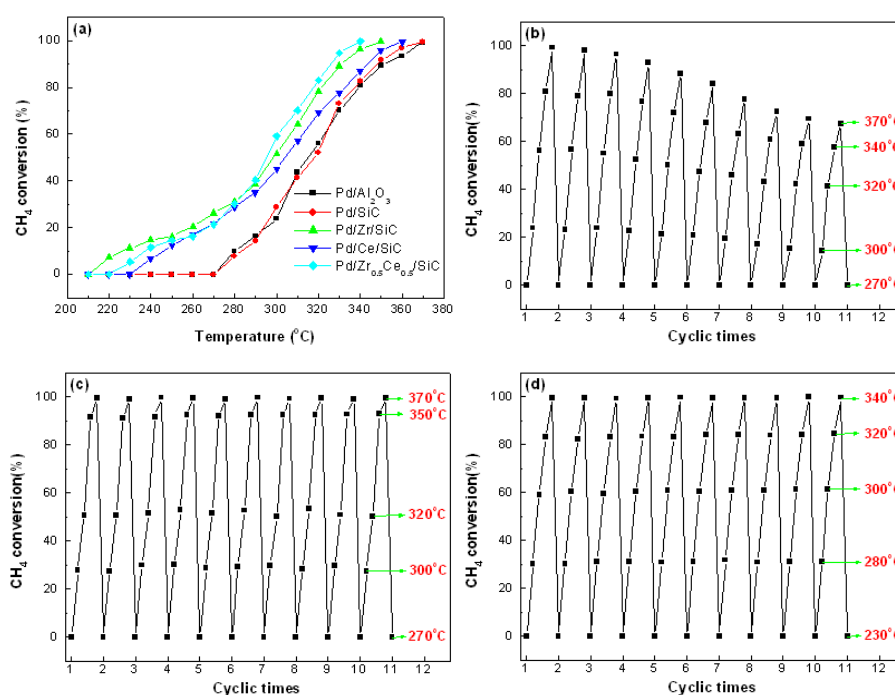


Fig. 5 Catalytic performances of different catalysts for methane combustion: the activities of different catalysts (a); and cyclic reaction results of Pd/Al₂O₃ (b), Pd/SiC (c) and Pd/Zr_{0.5}Ce_{0.5}O₂/SiC (d).