Efficient production of dihydroxyacetone from glycerol over a Pt/CeO$_2$-ZrO$_2$-Bi$_2$O$_3$/SBA-16 catalyst

Pil-Gyu Choi,† Naoyoshi Nunotani and Nobuhito Imanaka

Department of Applied Chemistry, Faculty of Engineering, Osaka University, Osaka, Japan

ABSTRACT

A Pt/CeO$_2$-ZrO$_2$-Bi$_2$O$_3$/SBA-16 catalyst was prepared to realize highly selective oxidation of glycerol to produce dihydroxyacetone (DHA). An active oxygen supply from the CeO$_2$-ZrO$_2$-Bi$_2$O$_3$ promoter effectively oxidized glycerol to produce DHA under moderate conditions (i.e. at 30°C without applied pressure). After a 4 h catalytic reaction using the Pt/CeO$_2$-ZrO$_2$-Bi$_2$O$_3$/SBA-16 catalyst, the DHA yield and selectivity rose to 76% and 84%, respectively.

1. Introduction

Glycerol is generated as a byproduct in the production of bio-diesel from lipids, such as vegetable oils, animal oils, and waste fats [1,2]. Today’s increasing production of bio-diesel is fueling growth in the supply of glycerol, leading to surplus production of glycerol. It is, therefore, important to transform the excess glycerol to valuable chemicals, such as dihydroxyacetone (DHA), glyceric acid, tartronic acid, and lactic acid. DHA is one of the especially important compounds due to its skin-browning effect without UV irradiation (i.e. its sunless tanning effect). Since this tanning is nontoxic and poses no risk of skin cancer derived from UV rays, DHA has been widely used for cosmetics.

Currently, DHA is commercially produced by a fermentation method. Glycerol was effectively oxidized to DHA using *Gluconobacter oxydans* with an 87–94% yield after ca. 32 h [3]; this process requires a long operation time, however, and strict controls of the pH, temperature, and dissolved oxygen concentration to control bacteria. Several selective oxidation methods have also been suggested for DHA production, including photo-catalyst [4], electro-catalyst [5,6], homogeneous catalyst [7,8], and heterogeneous catalyst methods [9–23]. From the viewpoint of determining a convenient process, heterogeneous catalysts have received attention as means of achieving the transformation. Among the heterogeneous catalysts investigated, a Pt-Bi bimetallic catalyst has been reported to show high DHA productivity [18–23]. While the exact reason for its high selectivity remains unclear, one reasonable possibility is the geometric effect of active sites, which may suppress the primary hydroxy group oxidation of glycerol due to blocking of the Pt surface by Bi and facilitate secondary hydroxy group oxidation [21]. In particular, Pt-Bi/MCM-41 (MCM-41: Mobile Composition of Matter No. 41) gives a high DHA yield of 55% and high DHA selectivity of 65% [22]. However, this high selective oxidation activity requires an elevated pressure (0.3 MPa) and temperature (80°C) over a period of 4 h. It is also reported that adsorption of Bi on the Pt catalyst from the soluble Bi species is effective in producing a geometric effect and high DHA selectivity of 64% under even moderate pressure (atmospheric pressure) at 60°C for 6 h, while the DHA yield is decreased to 19% [21].

Here, we focus on promoters that supply the platinum activator with an active oxygen species from inside the lattice. Ceria-zirconia (CeO$_2$-ZrO$_2$) solid solution is a well-known commercial promoter due to its oxygen release and storage abilities [24]. Because it requires elevated temperatures to work as a promoter, however, its usage is limited to specific applications (e.g. automotive exhaust catalysts). We have previously found that the introduction of bismuth oxide (Bi$_2$O$_3$) into the CeO$_2$-ZrO$_2$ lattice enhanced its oxygen release and storage abilities, because the formation of oxide ion vacancies through the low-valent Bi$^{3+}$ substitution facilitated the migration of oxide ions [25]. By combining the CeO$_2$-ZrO$_2$-Bi$_2$O$_3$ promoter and the Pt activator, we have effectively removed the harmful organic compound...
1,4-dioxane (38%) from the liquid phase at 80°C for 6 h under atmospheric pressure [26].

In this study, we selected the CeO$_2$-ZrO$_2$-Bi$_2$O$_3$ promoter with high oxygen release and storage abilities to realize efficient production of valuable DHA by the selective oxidation from glycerol under moderate conditions. Since the surface area is also a key issue in increasing active sites, we selected a mesoporous silica SBA-16 (Santa Barbara Amorphous No. 16) with a large surface area as a support to disperse the Pt activator and the CeO$_2$-ZrO$_2$-Bi$_2$O$_3$ promoter. We, therefore, prepared Pt/CeO$_2$-ZrO$_2$-Bi$_2$O$_3$/SBA-16 and investigated its glycerol conversion and DHA yield.

2. Experimental

SBA-16 (SBA) was synthesized according to the method in the previous study [27]. Pluronic F-127 (1.6 g) and 1,3,5-trimethylbenzene (1.1 mL) were dissolved into 0.2 mol·L$^{-1}$ hydrochloric acid (90 mL). After stirring at 35°C for 3 h, tetramethyl orthosilicate (7.1 mL) was added to the solution, and the solution was stirred further at 35°C for 20 h. The solution was subsequently poured into a Teflon bottle in a sealed brass vessel and heated at 140°C for 24 h. The solid product was collected by filtration, dried at room temperature for 12 h, and calcined at 400°C for 4 h in an air flow.

16 wt% Ce$_{0.68}$Zr$_{0.17}$Bi$_{0.15}$O$_{2.00}$/SBA-16 (CZB/SBA) was synthesized by the impregnation method. SBA (0.40 g) was dispersed into a stoichiometric mixture of 1.0 mol·L$^{-1}$ Ce(NO$_3$)$_3$ (0.30 mL), 0.1 mol·L$^{-1}$ ZrO(NO$_2$)$_2$ (0.73 mL), and 0.5 mol·L$^{-1}$ Bi(NO$_3$)$_3$ (0.13 mL) aqueous solutions, and 0.068 mol·L$^{-1}$ nitric acid aqueous solution (50 mL) was added, with the molar ratio of Ce:Zr:Bi controlled at 68:17:15. After the mixture was stirred at room temperature for 6 h, the solvent was vaporized at 180°C. The powder was ground in a mortar and calcined at 600°C for 1 h in an air atmosphere. For purposes of comparison, 16 wt% Ce$_{0.80}$Zr$_{0.20}$O$_{2.00}$/SBA-16 (CZB/SBA) was also synthesized via the same method, with Ce:Zr adjusted to 80:20.

Pt was dispersed on CZB/SBA and CZ/SBA using a colloidal solution of Pt in ethanol stabilized with polyvinylpyrrolidone (20 mL) via the impregnation method, with the amount of Pt adjusted to 7 wt%. After impregnation, the mixture was heated at 180°C to evaporate the solvent, ground in a mortar, and calcined at 500°C for 4 h in an air atmosphere. Hereinafter, 7 wt% Pt/16 wt% Ce$_{0.80}$Zr$_{0.20}$O$_{2.00}$/SBA-16 and 7 wt% Pt/16 wt% Ce$_{0.80}$Zr$_{0.20}$O$_{2.00}$/SBA-16 are denoted as Pt/CZB/SBA and Pt/CZ/SBA, respectively.

The composition of the catalysts was measured by X-ray fluorescence spectrometry (XRF; Supermini200, Rigaku). The Brunauer-Emmett-Teller (BET) surface area was measured at −196°C (Micromeritics Tristar 3000; Shimadzu) using nitrogen gas adsorption. The crystal structure was identified by X-ray powder diffraction (XRD; SmartLab, Rigaku) in the 20 range from 10 to 150 deg. using Cu Kα radiation (40 kV, 30 mA), and the XRD profiles were refined via the Rietveld method using the RIETAN-FP program [28]. The SBA pattern was used as a background for the Rietveld refinement and the occupations of each cation were estimated from the result of XRF. Transmission electron microscopy (TEM; H-800, Hitachi) was conducted to observe the morphology and size of the particles.

The oxidation of glycerol was conducted in batch mode in an air atmosphere using a mechanically stirred 300 mL three-necked flask. An aqueous solution of 1 wt% glycerol (10 mL) was poured into the flask, and the catalyst (0.3 g) and Bi(NO$_3$)$_3$·5H$_2$O were added, with the weight ratio of the Bi$^{3+}$ ions in Bi(NO$_3$)$_3$·5H$_2$O to the catalyst adjusted to 0, 0.075, 1, and 7.5 wt%. After the reaction at 30°C, the catalyst and liquid phase were separated by centrifugation (Allegra 64R centrifuge, Beckman Coulter). A sample of the liquid phase was mixed with naphthalene solution in methanol (5000 ppm) as an internal standard in a volume ratio of 1:2. This sample was analyzed by gas chromatograph mass spectrometry (GCMS; GCMS-QP2010 Plus; Shimadzu) to determine the amount of oxidized glycerol and DHA produced. For each analysis, 1 μL of the sample was injected, and the flow rate of helium was set to 1.3 mL·min$^{-1}$. Mass spectra were recorded in the mass range of 15–150 amu. The temperature of the injector was set to 240°C, and the column (Rtx-624, Restek) temperature program was set in the range of 50–230°C. The molar concentrations of the residual glycerol and the DHA produced after the reaction were estimated by comparison with the internal standard solution. Temperature-programmed reduction (TPR; Belcat-B, Microtrac BEL) measurement of the catalyst was performed under a flow of 5% H$_2$·95% Ar (50 mL·min$^{-1}$) at a heating rate of 5°C·min$^{-1}$.

3. Results and discussion

The composition and the BET surface area of the Pt/CZB/SBA and the Pt/CZ/SBA catalysts are tabulated in Table 1. The composition of the synthesized catalysts is shown in Table 1.

| Catalyst         | Measured composition | BET surface area/ m$^2$. g$^{-1}$ |
|------------------|----------------------|----------------------------------|
| Pt/CZB/SBA       | 7 wt%Pt/16 wt%Ce$_{0.80}$Zr$_{0.20}$O$_{2.00}$/SBA-16 | 461                              |
| Pt/CZ/SBA        | 7 wt%Pt/14 wt%Ce$_{0.80}$Zr$_{0.20}$Bi$_{0.15}$O$_{2.00}$/SBA-16 | 452                              |
catalysts was confirmed to be in good agreement with the stoichiometric ratio of the starting materials within the range of experimental error. Both Pt/CZ/SBA and Pt/CZB/SBA exhibited almost the same surface areas, which were smaller than that of SBA (787 m$^2$·g$^{-1}$). This result suggests that Pt and the promoters were successfully supported in SBA-16. Figure 1 shows the results of Rietveld refinement for the XRD patterns of the Pt/CZB/SBA and Pt/CZ/SBA catalysts. All the diffraction peaks were indexed as Pt and a cubic fluorite-type structure of CZB or CZ, and no impurity phase was observed. The structural parameters of fluorite-type CZB and CZ are summarized in Table 2. The lattice parameter of CZB was larger than that of CZ, indicating that the Ce$^{4+}$ (ionic radius: 0.097 nm [29]) and Zr$^{4+}$ (0.084 nm [29]) sites were successfully replaced with the larger Bi$^{3+}$ ions (0.117 nm [29]). In addition, the oxygen occupation was decreased by introducing lower-valent Bi$^{3+}$ ions into the CZ lattice (i.e. the oxide ion vacancies were increased).

Figure 2 shows TEM and electron diffraction images of the Pt/CZB/SBA catalyst. The Pt/CZB/SBA catalyst has a regular arrangement of pores with diameters of ca. 12 nm caused by SBA-16. The Pt particles were observed as dark spots in and/or on the mesopores of SBA-16. Although it is difficult to distinguish between CZB and SBA-16 in the TEM image, the electron diffraction image was clearly indexed as cubic fluorite-type CZB and Pt. Pt and CZB were, therefore, well dispersed in the mesopores of SBA-16. The catalytic performance of DHA production from glycerol was carried out using Pt/CZB/SBA and Pt/CZ/SBA at 30°C under atmospheric pressure. Figure 3 shows the glycerol conversion and the DHA yield as a function of reaction time. For Pt/CZB/SBA, the glycerol conversion increased with increases in the reaction time, and glycerol conversion was complete after reaction for 5 h. The DHA yield also increased with passage of the reaction time up to 4 h. After 4 h, although the glycerol conversion increased, the DHA yield decreased, suggesting that further oxidation of DHA was proceeding. Therefore, the highest DHA yield was obtained after reaction for 4 h, and the value reached a high of 76%. Thus, DHA selectivity was calculated as 84%. In the case of Pt/

![Figure 1](image1.png)  
*Figure 1. Results of Rietveld analysis of (a) Pt/CZB/SBA and (b) Pt/CZ/SBA.*

![Figure 2](image2.png)  
*Figure 2. TEM and electron diffraction images of the Pt/CZB/SBA catalyst.*

| Catalyst     | Lattice parameter /nm | Atom | Wyckoff Position | Occupation | x   | y   | z   | B/Å$^2$ |
|--------------|-----------------------|------|-----------------|------------|-----|-----|-----|---------|
| Pt/CZB/SBA   | 0.5426(1)             | Ce   | 4a              | 0.69       | 0   | 0   | 0   | 1       |
|              |                       | Zr   | 4a              | 0.16       | 0   | 0   | 0   | 1       |
|              |                       | Bi   | 4a              | 0.15       | 0   | 0   | 0   | 1       |
|              |                       | O    | 8c              | 0.847(7)   | 1/4 | 1/4 | 1/4 | 1       |
| Space group: |                       |      |                 |            |     |     |     |         |
| Fmm          | $R_{wp}$ = 5.20 %, S = 1.35 |

| Catalyst     | Lattice parameter /nm | Atom | Wyckoff Position | Occupation | x   | y   | z   | B/Å$^2$ |
|--------------|-----------------------|------|-----------------|------------|-----|-----|-----|---------|
| Pt/CZ/SBA    | 0.5383(1)             | Ce   | 4a              | 0.80       | 0   | 0   | 0   | 1       |
|              |                       | Zr   | 4a              | 0.20       | 0   | 0   | 0   | 1       |
|              |                       | O    | 8c              | 0.955(9)   | 1/4 | 1/4 | 1/4 | 1       |
| Space group: |                       |      |                 |            |     |     |     |         |
| Fmm          | $R_{wp}$ = 5.46 %, S = 1.35 |
CZ/SBA, while the glycerol conversion substantially increased with time, the DHA yields were below 10%. A comparison of Pt/CZB/SBA and Pt/CZ/SBA reveals that both the glycerol conversion and DHA yield were obviously enhanced by introducing \( \text{Bi}_2\text{O}_3 \) into the CZ lattice. The increase in the activity might be attributable to an effective supply of active oxygen from the CZB promoter.

TPR measurement was carried out to investigate oxygen release from the promoter. The TPR profiles of Pt/CZB/SBA and Pt/CZ/SBA are shown in Figure 4 with the data for SBA. At temperatures below 400°C, there was no peak in the profiles of SBA, indicating that SBA exhibits no reduction activity. For both catalysts, two reduction peaks were observed at ca. 250 and 320°C, which were designated as the reduction of PtO\(_2\) (lower temperature peak) and the surface reduction of Ce\(^{4+}\) in close contact with platinum particles (higher temperature peak) [30]. The first reduction temperature was lowered by introducing Bi\(_2\)O\(_3\) (i.e. Pt/CZB/SBA: 238°C and Pt/CZ/SBA: 245°C). In addition, the total amount of \( \text{H}_2 \) consumption for Pt/CZB/SBA (2.2 mmol·g\(^{-1}\)) was significantly higher than that for Pt/CZ/SBA (1.0 mmol·g\(^{-1}\)). This significant enhancement of \( \text{H}_2 \) consumption and the lowering of the reduction temperature suggest that an oxygen species was effectively released from the promoter through oxygen vacancies formed by the introduction of lower-valent Bi\(^{3+}\) ions into the CZ lattice.

In previous studies, Pt-Bi bimetallic catalysts were reported for selective oxidation of glycerol due to the geometric effect [18–23]. According to Yang et al. [21], a Pt catalyst supported on NCNT (N-doped carbon nanotubes) was successfully activated by adding a 1 wt% soluble Bi species (Bi\(^{3+}\)) to Pt/NCNT during a catalytic reaction via conducted formation of Pt-Bi active sites, which was more effective in producing DHA than a pre-loaded PtBi catalyst. In the case of the Pt/CZB/SBA catalyst, there is a possibility that Bi\(^{3+}\) ions are leached from the CZB promoter and affect the catalytic activity; therefore, the effect of Bi\(^{3+}\) ions on Pt/CZ/SBA’s catalytic performance was investigated. Table 3 shows the catalytic activity of Pt/CZ/SBA with the soluble Bi species, where the added Bi content is the weight percentage of the Bi\(^{3+}\) ions in Bi(NO\(_3\))\(_3\)·5H\(_2\)O based on the Pt/CZ/SBA catalyst and which has changed from 0.075 wt% (Bi\(^{3+}\):Pt molar ratio of 1:100) to 7.5 wt% (Bi\(^{3+}\):Pt molar ratio = 1:1). In the presence of 0.075 wt% of Bi\(^{3+}\) ions, the glycerol conversion and the DHA yield were increased. These enhancements might be attributable to the geometric effect; that is, chelation between glycerol and Pt-Bi sites and blocking of Pt’s high energy might accelerate selective oxidation [15,21,31]. With increases in the soluble Bi content, both the glycerol conversion and DHA yield decreased, suggesting that a strong blocking effect interrupted the glycerol oxidation. The highest DHA yield (25%) was obtained in the case of the 0.075 wt% Bi addition; this value was considerably lower than that of Pt/CZB/SBA (76%), however, regardless of the almost identical glycerol conversion. By adding 1 wt% Bi\(^{3+}\), in a way similar to that reported in the previous paper [21], DHA selectivity rose to 50%, while selectivity was also low.

### Table 3. Catalytic performance over the Pt/CZ/SBA catalyst with Bi(NO\(_3\))\(_3\)·5H\(_2\)O after the reaction at 30°C for 4 h.

| Added Bi content* /wt% | Glycerol conversion /% | DHA yield /% | DHA selectivity /% |
|------------------------|------------------------|--------------|--------------------|
| 0                      | 66                     | 3            | 5                  |
| 0.075                  | 84                     | 25           | 30                 |
| 1                      | 36                     | 18           | 50                 |
| 7.5                    | 24                     | 0            | 0                  |

*Added Bi content is the weight percentage of the Bi\(^{3+}\) ions in Bi(NO\(_3\))\(_3\)·5H\(_2\)O based on the Pt/CZ/SBA catalyst.
compared to that of Pt/CZB/SBA (84%). Based on these results, it is considered that selective oxidation with the Pt/CZB/SBA catalyst might be attributable to another mechanism, except for the leaching of the soluble Bi species from CZB. It is expected that glycerol chelated with surface Bi$^{3+}$ ions in CZB in addition to the Pt activator, and that this chelation effect and the supply of the active oxygen species from the CZB promoter facilitated oxidation of glycerol by the secondary hydroxy group.

4. Conclusions

The Pt/CeO$_2$-ZrO$_2$-Bi$_2$O$_3$/SBA-16 catalyst was prepared via an impregnation method for the selective oxidation of glycerol to produce DHA. The catalyst possesses a large surface area, and Pt and CeO$_2$-ZrO$_2$-Bi$_2$O$_3$ were well dispersed in and/or on SBA-16. Introducing Bi$_2$O$_3$ into the CeO$_2$-ZrO$_2$ lattice enhanced the ability to release oxygen due to an increase in the oxygen vacancies allowing oxide ion migration. The catalytic oxidation of glycerol was performed under moderate conditions of 30°C under atmospheric pressure. The Pt/CeO$_2$-ZrO$_2$-Bi$_2$O$_3$/SBA-16 catalyst exhibited activity for efficient DHA production from glycerol, likely due to effective supply of the active oxygen species from the promoter and the geometric effect among Pt, the surface Bi$^{3+}$ ions in the promoter, and the reactant. After reaction for 4 h, the high DHA yield and selectivity rose to 76% and 84%, respectively.

Acknowledgments

A part of the experiments in the study were conducted in a facility in the Osaka University Research Center for Ultra-High Voltage Electron Microscopy, and we thank Dr. Takao Sakata and Prof. Hidehiro Yasuda of the Center for helping us with the TEM measurements. We also thank Mr. Masanari Takashima of Osaka University for assisting us with the catalytic activity measurements.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Japan Soap and Detergent Association.

ORCID

Pil-Gyu Choi  http://orcid.org/0000-0003-0439-8426
Naoyoshi Nunotani  http://orcid.org/0000-0001-5497-9777
Nobuhito Imanaka  http://orcid.org/0000-0003-1243-9099

References

[1] Yang F, Hanna MA, Sun R. Value-added uses for crude glycerol-a byproduct of biodiesel production. Biotechnol Biofuels. 2012;5(13):1–10.
[2] Bagheri S, Julkapli NM, Yehye WA. Catalytic conversion of biodiesel derived raw glycerol to value added products. Renew Sust Energ Rev. 2015;41:113–127.
[3] Švitej J, Šturdík E. Product yield and by-product formation in glycerol conversion to dihydroxyacetone by Gluconobacter oxydans. J Ferment Bioeng. 1994;78:351–355.
[4] Zhang Y, Zhang N, Tang Z, et al. Identification of Bi$_2$WO$_6$ as a highly selective visible light photocatalyst toward oxidation of glycerol to dihydroxyacetone in water. Chem Sci. 2013;4:1820–1824.
[5] Kwon Y, Birdja Y, Spanos I, et al. Highly selective electro-oxidation of glycerol to dihydroxyacetone on platinum in the presence of bismuth. ACS Catal. 2012;2:759–764.
[6] Lee S, Kim HJ, Lim EJ, et al. Highly selective transformation of glycerol to dihydroxyacetone without using oxidants by a PtSb/C-catalyzed electrooxidation process. Green Chem. 2016;18:2877–2887.
[7] Painter RM, Pearson DM, Waymouth RM. Selective catalytic oxidation of glycerol to dihydroxyacetone. Angew Chem Int Ed. 2010;49:9456–9459.
[8] Zheng Z, Luo M, Yu J, et al. Novel process for 1,3-dihydroxyacetone production from glycerol. 1. Technological feasibility study and process design. Ind Eng Chem Res. 2012;51:3715–3721.
[9] Liang D, Gao J, Wang J, et al. Selective oxidation of glycerol in a base-free aqueous solution over different sized Pt catalysts. Catal Commun. 2009;10:1586–1590.
[10] Hirasa S, Nakagawa Y, Tomishige K. Selective oxidation of glycerol to dihydroxyacetone over a Pd-Ag catalyst. Catal Sci Technol. 2012;2:1150–1152.
[11] Xu J, Zhang H, Zhao Y, et al. Selective oxidation of glycerol to lactic acid under acidic conditions using AuPd/TiO$_2$ catalyst. Green Chem. 2013;15:1520–1525.
[12] Kondrat SA, Miedziak PJ, Douthwaite M, et al. Base-free oxidation of glycerol using titania-supported trimetallic Au-Pd-Pt nanoparticles. ChemSusChem. 2014;7:1326–1334.
[13] Liu S, Sun K, Xu B. Specific selectivity of Au-catalyzed oxidation of glycerol and other C$_3$-polyols in water without the presence of a base. ACS Catal. 2014;4:2226–2230.
[14] Meng Y, Zou S, Zhou Y, et al. Activating molecular oxygen by Au/ZnO to selectively oxidize glycerol to dihydroxyacetone. Catal Sci Technol. 2018;8:2524–2528.
[15] Kimura H, Tsuto K, Wakisaka T, et al. Selective oxidation of glycerol on a platinum-bismuth catalyst. Appl Catal A Gen. 1993;96:217–228.
[16] Kimura H. Selective oxidation of glycerol on a platinum-bismuth catalyst by using a fixed bed reactor. Appl Catal A Gen. 1993;105:147–158.
[17] Garcia R, Besson M, Gallezot P. Chemoselective catalytic oxidation of glycerol with air on platinum metals. Appl Catal A Gen. 1995;127:165–176.
[18] Hu W, Knight D, Lowry B, et al. Selective oxidation of glycerol to dihydroxyacetone over Pt-Bi/C catalyst: optimization of catalyst and reaction conditions. Ind Eng Chem Res. 2010;49:10876–10882.
[19] Wörz N, Brandner A, Claus P. Platinum-bismuth-catalyzed oxidation of glycerol: kinetics and the origin of selective deactivation. J Phys Chem C. 2010;114:1164–1172.
[20] Villa A, Campisi S, Chan-Thaw CE, et al. Bismuth modified Au-Pt bimetallic catalysts for dihydroxyacetone production. Catal Today. 2015;249:103–108.

[21] Ning X, Li Y, Yu H, et al. Promoting role of bismuth and antimony on Pt catalysts for the selective oxidation of glycerol to dihydroxyacetone. J Catal. 2016;335:95–104.

[22] Xiao Y, Greeley J, Varma A, et al. An experimental and theoretical study of glycerol oxidation to 1,3-dihydroxyacetone over bimetallic Pt-Bi catalysts. Aiche J. 2017;63:705–715.

[23] Xue W, Wang Z, Liang Y, et al. Promoting role of bismuth on hydrotalcite-supported platinum catalysts in aqueous phase oxidation of glycerol to dihydroxyacetone. Catalysts. 2018;8(20):1–12.

[24] Montini T, Melchionna M, Monai M, et al. Fundamentals and catalytic applications of CeO$_2$-based materials. Chem Rev. 2016;116:5987–6041.

[25] Imanaka N, Masui T, Koyabu K, et al. Significant low-temperature redox activity of Ce$_{0.64}$Zr$_{0.16}$Bi$_{0.20}$O$_{1.90}$ supported on γ-Al$_2$O$_3$. Adv Mater. 2007;19:1608–1611.

[26] Choi PG, Ohno T, Fukuhara N, et al. Catalytic liquid phase oxidation of 1,4-dioxane over a Pt/CeO$_2$-ZrO$_2$-Bi$_2$O$_3$/SBA-16 catalyst. J Adv Ceram. 2015;4:71–75.

[27] Yotou H, Okamoto T, Ito M, et al. Novel method for insertion of Pt/CeZrO$_2$ nanoparticles into mesoporous SBA-16 using hydrothermal treatment. Appl Catal A Gen. 2013;458:137–144.

[28] Izumi F, Momma K. Three-dimensional visualization in powder diffraction. Solid State Phenom. 2007;130:15–20.

[29] Shannon RD. Revised effective ionic radii and systematic studies of interatomic distances in halides and chalcogenides. Acta Crystallogr, Sect A. 1976;32:751–767.

[30] Bi YD, Zhang W, Xu HY, et al. Nanocrystalline CeO$_2$ in SBA-15: performance of Pt/CeO$_2$/SBA-15 catalyst for water-gas-shift reaction. Catal Lett. 2007;119:126–133.

[31] Mondelli C, Ferri D, Grunwaldt J, et al. Combined liquid-phase ATR-IR and XAS study of the Bi-promotion in the aerobic oxidation of benzyl alcohol over Pd/Al$_2$O$_3$. J Catal. 2007;252:77–87.