Effect of Cs–Ce–Zr Catalysts/Soot Contact Conditions on Diesel Soot Oxidation

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ABSTRACT: Cs–Ce–Zr catalysts with various weight ratios are prepared by the sol–gel method in this paper. The main crystalline phases were identified by X-ray diffraction. The activities of catalysts during soot combustion were tested by thermogravimetric and differential scanning calorimetry. The contact conditions of soot/catalysts (sintered at 450 and 380 °C, respectively, under loose and tight contact conditions) were observed by scanning electron microscopy to study the effect of contact conditions on catalytic activity, and it was determined that the catalytic activities under tight contact conditions are superior to those under loose contact conditions. However, the soot oxidation rate speeds up after the peak temperature of about 450 °C under loose contact conditions, which is due to the fact that the contact condition is enhanced by melting CsNO3. The soot onset ignition temperature is lower for the catalysts with more Cs content under loose contact conditions. The minimum gaps of the soot onset ignition temperature and soot oxidation rates under the two contact conditions are 32 and 7 °C, which shows that the gap of catalytic activities under the respective contact conditions can be decreased by the formation of different crystalline phases.

INTRODUCTION

Soot particulates discharged by diesel engines have caused serious pollution. The use of diesel particulate filters (DPFs) seems a better way to solve the pollution problem. To assure the regeneration of DPFs, a potentially useful catalyst has to operate efficiently at low temperatures because the temperature of typical exhausts is 400 °C or below in light-duty applications.1 Also, the contact condition between soot and catalysts is a major factor which lowers the catalytic activity of catalysts.2,3 CeO2−x(O) catalysts have been applied widely in three-way catalysts for gasoline engines. The popularity of CeO2 is mostly due to its number of effective redox Ce4+/Ce3+ sites and its ability to exchange oxygen. The oxygen vacancy in CeO2 due to many Ce4+/Ce3+ redox sites can be rapidly formed and removed, which results in its remarkable oxygen storage capacity.4−6 The Zr substitution of Ce by Zr is considered a modification of the reduction of Ce4+ and the mobility of lattice oxygen.6 Ceria nanofibers were synthetized as soot oxidation catalysts, which can reduce the peak combustion temperature from 600 °C (noncatalytic combustion) to 375 °C in tight contact and 533 °C in loose contact.4 Ce1−xZrxO2 had been prepared by the sol–gel method and shifting the combustion temperature (Tm) from 622 to 547 °C (loose contact) or 404 °C (tight contact).7 CuO/ceria–zirconia catalysts have been prepared and displayed a very high activity (54% at 348 °C).8 The effects of Nd doping on the physicochemical and catalytic properties for soot combustion of CeO2 and CeO2−xZrO2 oxides have been studied.9 Three-dimensionally ordered macroporous Ce1−xZrxO2-supported gold nanoparticle catalysts were successfully synthesized by the gas bubbling-assisted membrane reduction method.10 A series of ceria and ceria–zirconia catalysts with varying compositions and surface areas have been systematically investigated in the oxidation of soot in the temperature range of 600 K < T < 800 K.11 K–Ce–Zr had been prepared and showed good catalytic activity for soot oxidation under loose contact conditions.12 In the case of soot oxidation, the first role of alkali is to reinforce the contact between soot particles and the catalyst surface since this parameter is known as a critical step in soot oxidation reactions.13−16 According to the relative study, the order of reactivity of alkaline for soot oxidation is: Cs > K > Na.17 Some catalysts containing Cs for soot combustion have been studied, including the Cs–Cu/ZrO2 system,18 Cs0.5−M0.5/ZrO2 catalysts (M = Cu or Co),19 Cs0.5−MnO0.5−CeO2 catalysts,20 Cs2SO4·V2O5 catalysts,21 and so forth. The Cs–Ce–Zr catalysts had been prepared by the sol–gel method, and the effects of contact conditions between soot and catalysts on soot catalytic combustion have been discussed in this paper.

RESULTS AND DISCUSSION

Powder X-ray Diffraction (XRD) Analysis. XRD patterns of Cs–Ce–Zr catalysts with different weight ratios have been presented in Figure 1. The main crystalline phases are listed in Table 1. It can be seen that the main crystalline phases are CsNO3, ZrO2Ce0.8O2, and Cs0.5ZrO4 for sample 1. Sample 2 has...
three crystalline phases of CsNO$_3$, Zr$_{0.4}$Ce$_{0.6}$O$_2$, and Cs$_4$ZrO$_4$. There are three identical phases of CsNO$_3$, Cs$_4$ZrO$_4$, and CeO$_2$ for sample 3, sample 4, and sample 5. The distinct phases are Zr$_{0.5}$Ce$_{0.5}$O$_2$, Zr$_{0.4}$Ce$_{0.6}$O$_2$, and CeO$_2$ for above three catalysts. Sample 6 contains Cs$_4$ZrO$_4$, CsNO$_3$, and Zr$_{0.5}$Ce$_{0.5}$O$_2$. The same phase Zr$_{0.5}$Ce$_{0.5}$O$_2$ is presented when sample 2 and sample 3 are with an identical Ce–Zr molar ratio of 1:1. This illustrates that the formation of cerium zirconium compounds is not affected by the Cs content. Sample 1 and sample 4 with the same Ce–Zr molar ratio of 2:1 presented the same phase Zr$_{0.5}$Ce$_{0.5}$O$_2$. However, sample 5 with a molar ratio of 3:2:1 contains the different phase Ce$_{0.75}$Zr$_{0.25}$O$_2$. This illustrates that the cerium zirconium compounds will be affected when the Cs content is beyond a certain value. All six catalysts contain CsNO$_3$.

**Table 1. Main Crystalline Phases on XRD Patterns**

| catalysts | crystalline phases                  |
|-----------|------------------------------------|
| sample 1  | CsNO$_3$, Zr$_{0.5}$Ce$_{0.5}$O$_2$, Cs$_4$ZrO$_4$ |
| sample 2  | CsNO$_3$, Zr$_{0.5}$Ce$_{0.5}$O$_2$, Cs$_4$ZrO$_4$ |
| sample 3  | CsNO$_3$, Zr$_{0.5}$Ce$_{0.5}$O$_2$, Cs$_4$ZrO$_4$, CeO$_2$ |
| sample 4  | CsNO$_3$, Zr$_{0.5}$Ce$_{0.5}$O$_2$, Cs$_4$ZrO$_4$, CeO$_2$ |
| sample 5  | CsNO$_3$, Ce$_{0.75}$Zr$_{0.25}$O$_2$, Cs$_4$ZrO$_4$, CeO$_2$ |
| sample 6  | CsNO$_3$, Zr$_{0.5}$Ce$_{0.5}$O$_2$, Cs$_4$ZrO$_4$, CeO$_2$ |

Thermogravimetric and Differential Scanning Calorimetry (TG–DSC) Analysis. The TG–DSC curves of the Cs–Ce–Zr catalysts and soot under loose contact conditions have been shown in Figure 2, and their parameters of catalytic activity are shown in Table 2. It can be seen from Figure 2 and Table 2 that sample 5 and sample 6 have the lowest soot onset ignition temperature of 345 °C, and their soot oxidation rates are the slowest among the six catalysts. $T_o$ is 350 °C for sample 3, which is lower among the six catalysts. It can be seen from Table 2 that the lower $T_o$ may be caused by the higher Cs content of 53.61, 51.80, and 55.3% for sample 3, sample 5, and sample 6. Sample 4 has the fastest soot oxidation rate, but its soot onset ignition temperature is higher. $T_o$ is similar and $\Delta T$ has a gap of 10 °C for sample 1 and sample 4, which shows that the appearance of Cs$_4$ZrO$_4$ and CeO$_2$ for sample 4 has less effect on catalytic activity. Soot onset ignition is lowered 14 °C and the soot oxidation rate is slowed 10 °C for sample 3 than those of sample 1. It can be seen from Table 1 that sample 2 and sample 3 have three same phases of CsNO$_3$, Zr$_{0.5}$Ce$_{0.5}$O$_2$, and Cs$_4$ZrO$_4$, but only sample 3 possesses CeO$_2$. It can be seen from Tables 1 and 2 that formations of cerium zirconium compounds have little effect on catalytic activity of the six catalysts under loose contact conditions. The catalysts have the optimum catalytic activity when the catalysts have the proper ratios of Cs–Ce–Zr.

TG–DSC curves of the Cs–Ce–Zr catalysts and soot mixtures under tight contact mode have been presented in Figure 3. It can be seen from Figures 2 and 3 that there are small weight losses on TG curves between 100 and 200 °C, for which no corresponding peaks are shown on DSC curves. Also, it can be seen that the weight loss is increased when the catalysts contain more Cs content. As can be seen from Table 1, all the crystalline phases are very stable below 200 °C, so the weight loss cannot be due to the decomposition of the main crystalline phases. CsNO$_3$ can absorb moisture in air, and the catalysts containing CsNO$_3$ may absorb CO$_2$ in air. Therefore, it can be concluded that the weight loss may be due to the volatilization of physical adsorption of water or desorption of CO$_2$ adsorbed on the surface of catalysts. The parameters of catalytic activity for the Cs–Ce–Zr catalysts with soot under tight contact conditions have been shown in Table 3. Comparing Table 2 with Table 3, $T_o$ is lowered and the soot oxidation rate is quickened obviously for a majority of catalysts under tight contact conditions than under loose contact conditions. It can be seen from Figure 3 and Table 3 that sample 5 has the lowest $T_o$ of 294 °C among the six catalysts under tight contact conditions, which is lowered 51 °C than under loose contact conditions. Sample 2 has the highest $T_o$ of 332 °C among the six catalysts. Sample 6 has the fastest soot oxidation rate under tight contact conditions, which is quickened 41 °C than under loose contact conditions. Sample 1 has the lowest soot oxidation rate under tight contact conditions, which is similar under loose contact conditions. This illustrates that the soot oxidation rate is not affected by contact mode under cooperation of CsNO$_3$ and Zr$_{0.5}$Ce$_{0.5}$O$_2$. Sample 1 has $T_o$ similar to sample 4 under tight contact conditions, which shows that cooperation of CsNO$_3$ and Zr$_{0.5}$Ce$_{0.5}$O$_2$ is similar with CsNO$_3$, Zr$_{0.4}$Ce$_{0.6}$O$_2$, Cs$_4$ZrO$_4$, and CeO$_2$ on lowering $T_o$. The soot oxidation rate is the gap of 15 °C under CsNO$_3$, Zr$_{0.4}$Ce$_{0.6}$O$_2$, Cs$_4$ZrO$_4$, and CeO$_2$ compared to CsNO$_3$ and Zr$_{0.5}$Ce$_{0.5}$O$_2$. The gap is not large. Sample 2 has
a soot oxidation rate similar to sample 3. However, $T_o$ has a gap of 14 °C, which shows that more Cs content and appearance of CeO$_2$ has little effect on catalytic activity under tight contact conditions. Under CsNO$_3$ and Zr$_{0.4}$Ce$_{0.6}$O$_2$ for sample 1, CsNO$_3$, Zr$_{0.4}$Ce$_{0.6}$O$_2$, Cs$_4$ZrO$_4$, and CeO$_2$ for sample 4, and CsNO$_3$, Ce$_{0.75}$Zr$_{0.25}$O$_2$, Cs$_4$ZrO$_4$, and CeO$_2$ for sample 5, $T_o$ is lowered over 50 °C under tight contact conditions rather than under loose contact conditions. $T_o$ is lowered over 30 °C under tight contact conditions rather than under loose contact conditions under CsNO$_3$, Zr$_{0.4}$Ce$_{0.6}$O$_2$, and Cs$_4$ZrO$_4$ for sample 2, Cs$_{4}$ZrO$_4$, Zr$_{0.16}$Ce$_{0.84}$O$_2$, and CeO$_2$ for sample 3, and Cs$_{4}$ZrO$_4$, Zr$_{0.4}$Ce$_{0.6}$O$_2$, and Cs$_4$ZrO$_4$ for sample 6. Soot oxidation is not affected nearly as much by contact mode under CsNO$_3$ and Zr$_{0.4}$Ce$_{0.6}$O$_2$ for sample 1. Soot oxidation is affected slightly under CsNO$_3$, Zr$_{0.5}$Ce$_{0.5}$O$_2$, Cs$_4$ZrO$_4$, and CeO$_2$, and the gap of $\Delta T$ is only 12 °C for sample 4 under the two contact modes. The gap of $\Delta T$ is 19 °C under CsNO$_3$, Zr$_{0.5}$Ce$_{0.5}$O$_2$, and Cs$_4$ZrO$_4$ for sample 2 under the two contact modes. The gap of $\Delta T$ is 35 °C under CsNO$_3$, Zr$_{0.3}$Ce$_{0.7}$O$_2$, Cs$_4$ZrO$_4$, and CeO$_2$ for sample 3 and 32 °C under CsNO$_3$, Ce$_{0.75}$Zr$_{0.25}$O$_2$, Cs$_4$ZrO$_4$, and CeO$_2$ for sample 5 under the two contact modes. The gap is 41 °C under CsNO$_3$, Zr$_{0.4}$Ce$_{0.6}$O$_2$, and Cs$_4$ZrO$_4$ for sample 6 under the two contact modes. The orders of crystalline phases which $T_o$ is affected by contact mode from small to large are as follows: CsNO$_3$ + Zr$_{0.5}$Ce$_{0.5}$O$_2$ + Cs$_4$ZrO$_4$ (sample 2) $\approx$ CsNO$_3$ + Zr$_{0.4}$Ce$_{0.6}$O$_2$ + Cs$_4$ZrO$_4$ + CeO$_2$ (sample 3) $\approx$ CsNO$_3$ + Zr$_{0.84}$Ce$_{0.16}$O$_2$ + Cs$_4$ZrO$_4$ (sample 6) $<$. CsNO$_3$ + Zr$_{0.4}$Ce$_{0.6}$O$_2$ (sample 1) $\approx$. CsNO$_3$ + Ce$_{0.75}$Zr$_{0.25}$O$_2$ + Cs$_4$ZrO$_4$ + CeO$_2$ (sample 5) $<$. CsNO$_3$ + Zr$_{0.4}$Ce$_{0.6}$O$_2$ + Cs$_4$ZrO$_4$ + CeO$_2$ (sample 4).

Figure 2. TG–DSC curves of the Cs–Ce–Zr catalysts and soot mixtures under loose contact mode. (a) Sample 1, (b) sample 2, (c) sample 3, (d) sample 4, (e) sample 5, and (f) sample 6.

Table 2. Parameters of Catalytic Activity for Cs–Ce–Zr Catalysts with Soot under Loose Contact Conditions

| catalysts | $T_o$ (°C) | $T_p$ (°C) | $\Delta T$ (°C) | $T_e$ (°C) |
|-----------|------------|------------|----------------|------------|
| sample 1  | 360        | 448        | 88             | 481        |
| sample 2  | 364        | 451        | 89             | 490        |
| sample 3  | 350        | 447        | 79             | 490        |
| sample 4  | 362        | 440        | 78             | 489        |
| sample 5  | 345        | 452        | 107            | 495        |
| sample 6  | 345        | 444        | 99             | 488        |

Table 2. Parameters of Catalytic Activity for Cs–Ce–Zr Catalysts with Soot under Loose Contact Conditions

| catalysts | $T_o$ (°C) | $T_p$ (°C) | $\Delta T$ (°C) | $T_e$ (°C) |
|-----------|------------|------------|----------------|------------|
| sample 1  | 360        | 448        | 88             | 481        |
| sample 2  | 364        | 451        | 89             | 490        |
| sample 3  | 350        | 447        | 79             | 490        |
| sample 4  | 362        | 440        | 78             | 489        |
| sample 5  | 345        | 452        | 107            | 495        |
| sample 6  | 345        | 444        | 99             | 488        |
Scanning Electron Microscopy (SEM) Analysis. Figure 4 shows the morphology of the soot particulates. As can be seen from this figure, the soot particles have a particle size of about 50 nm in diameter and agglomerate together. The morphology of soot particles is close to sphere shape.

The SEM images of sample 1 and soot mixtures under two different contact conditions have been presented in Figure 5. It can be seen from Figure 5a that soot agglomerate together and the surfaces of some catalysts are not covered by soot when catalysts/soot are under loose contact conditions. However, Figure 5b shows that only gathered soot can be seen, which illustrates that catalysts have been covered fully by soot.

The SEM images of Cs–Ce–Zr catalysts and soot mixtures under tight contact conditions sintered at 450 °C have been presented in Figure 6a,c,e,g,i,k, which show that soot cannot be seen nearly and the surface of catalysts have become visible clearly. Figure 6b,d,f,h,j,l presented the SEM images of catalysts and soot mixtures under tight contact conditions sintered at

Table 3. Parameters of Catalytic Activity for Cs–Ce–Zr Catalysts with Soot under Tight Contact Conditions

| Catalysts | \( T_o \) (°C) | \( T_p \) (°C) | \( \Delta T \) (°C) | \( T_e \) (°C) |
|-----------|---------------|---------------|----------------|-------------|
| sample 1  | 308           | 389           | 81             | 462         |
| sample 2  | 332           | 400           | 68             | 475         |
| sample 3  | 318           | 380           | 62             | 463         |
| sample 4  | 302           | 368           | 66             | 456         |
| sample 5  | 294           | 369           | 75             | 464         |
| sample 6  | 312           | 370           | 58             | 472         |

Figure 3. TG–DSC curves of Cs–Ce–Zr catalysts and soot mixtures under tight contact mode. (a) Sample 1, (b) sample 2, (c) sample 3, (d) sample 4, (e) sample 5, and (f) sample 6.
380 °C, which can be seen that there is still some soot left over the surface of catalysts. It can be seen from Figure 2 and Table 2 that \( T_p \) is about 450 °C for the six catalysts with soot under loose contact conditions. It can be seen that the difference value of \( T_e \) and \( T_p \) is about 33–49 °C and that the difference value of \( T_p \) and \( T_o \) is about 78–107 °C, which shows that the soot.
combustion rate is quickened obviously after $T_p$. The melting temperature of CsNO$_3$ is 414 °C, and thus, the melting CsNO$_3$ can enhance the contact between soot and catalysts after 414 °C. Because catalysts and soot under loose contact conditions are sintered at 450 °C, which exceeds the melting temperature of CsNO$_3$. The soot combustion rate is fast under the action of melting CsNO$_3$, so very little soot remains on the surface of catalysts. There may be some residue soot integrated with melting CsNO$_3$, so the remnant soot is not seen in Figure 6.

Figure 3 and Table 3 show that the peak temperature of soot combustion is about 380 °C under tight contact conditions. It can be seen that the difference value of $T_o$ and $T_p$ is about 73–102 °C and that the difference value of $T_o$ and $T_p$ is about 58–81 °C, which shows that the soot combustion rate is slowed after $T_p$. The catalysts and soot mixtures under tight contact conditions sintered at 380 °C, at which CsNO$_3$ does not melt. Therefore, it can be seen from Figure 6b,d,f,h,j that there is a part of the soot remaining on the surface of catalysts. It can be seen that the role of unmelted CsNO$_3$ is very important at lowering the soot onset ignition temperature under tight contact conditions, but the effect on quickening the soot oxidation rate is not obvious.

**CONCLUSIONS**

The Cs−Ce−Zr catalysts with different weight ratios have been prepared by the sol–gel method. The compositions and catalytic activity have been studied. In addition, the effects of catalysts/soot contact conditions on catalytic activity have been researched. The soot onset ignition temperature is lowered, and the soot oxidation rate is quicker under tight contact conditions than that under loose contact conditions. The soot onset ignition temperature for the catalyst with $5.180$ Cs content is 294 °C under tight contact conditions, which is lowered about 50 °C when compared with that of loose contact conditions. Soot oxidation for the catalyst with $5.300$ Cs content is quickened about 40 °C under tight contact conditions when compared with that under loose contact conditions. The soot onset ignition temperature is affected slightly by contact mode under the cooperation of CsNO$_3$−ZrO$_2$,Ce$_x$O$_y$−Cs$_2$ZrO$_4$. Also, the soot oxidation rate is not affected nearly as much by contact mode under cooperation of CsNO$_3$−ZrO$_2$,Ce$_x$O$_y$. Soot oxidation can be sped up when the temperature exceeds the melting temperature of CsNO$_3$. Because the melting CsNO$_3$ can enhance the contact between soot and catalysts, the soot oxidation is accelerated obviously after 414 °C. The formations of different cerium zirconium compounds have little effect on catalytic activity. The catalytic activities depend on mainly the relative content of Cs−Ce−Zr.

**EXPERIMENTAL SECTION**

**Catalyst Preparation.** The analytical pure CsNO$_3$, Ce(NO$_3$)$_3$·6H$_2$O, and Zr(NO$_3$)$_4$·5H$_2$O were applied in this paper. The Cs−Ce−Zr catalysts with different weight ratios have been prepared by the sol–gel method. The theoretical compositions of the Cs−Ce−Zr catalysts are shown in Table 4. The analytical pure CsNO$_3$, Ce(NO$_3$)$_3$·6H$_2$O, and Zr(NO$_3$)$_4$·5H$_2$O with different molar ratios were dissolved in water, and the solutions were agitated at 80 °C via electromagnetic stirring, and a certain amount of citric acid and polyethylene glycol were added to the solution until the sols were formed. The sols were sealed and aged to form gels. The gels were dried at 120 °C for 4 h. At last, the dried catalyst samples were ground in an agate mortar, and then the samples were calcined at 600 °C for 2 h.

**Catalytic Oxidation Activity Characterization.** TG–DSC (STA 449C, NETZSCH, Germany) was used to characterize the catalytic activity of the prepared catalysts. The catalysts and soot were mixed in two modes to obtain the samples used in TG–DSC analysis. The loose contact mode samples were prepared as follows: the catalysts and soot were mixed and shaken gently to make the catalysts and soot mix in a uniform manner. The catalysts and soot were mixed and ground in an agate mortar to achieve the other kind of samples with tight contact mode used in TG–DSC testing. The soot used in the TG–DSC experiment was collected using glassware above the burning diesel oil. The thermal analyses were carried out at a heating rate of 10 °C/min from room temperature to 600 °C in air. CO$_2$ was released when the soot was oxidized under the action of the catalysts, so the weight loss would be presented on TG curves. The beginning temperature of weight loss $T_p$ is defined as the soot onset ignition temperature. $T_p$ is the peak temperature on DSC curves, which represents the maximum reaction rate of soot. $T_o$ is the temperature at which the loss weight was ended on TG curves.

$$\Delta T = T_p - T_o$$  

(1)

Hence, $T_o$ and $\Delta T$ were used to assess the catalytic activities of the catalysts. Less $\Delta T$ means that the soot oxidation occurs in a more rapid manner.

**Catalyst Structure Characterization.** Crystalline phases of the catalyst materials were identified by XRD (Rigaku D/max-rA, Rigaku, Japan) equipped with a Cu Kα radiation source. The contact condition between the soot and catalysts was observed by SEM (JSM-6700, JEOL Ltd. Japan). The samples for SEM had been prepared by mixing the catalysts and soot at a ratio of 3:1 under loose contact mode and tight contact mode. One sample was observed directly by SEM, and the other samples were placed at a furnace and heated to the 380 °C (under tight contact mode) and 450 °C (under loose contact mode) and then cooled to room temperature and observed by SEM.

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**Notes**

The authors declare no competing financial interest.
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REFERENCES
(1) Querini, C. A.; Cornaglia, L. M.; Ulla, M. A.; Miró, E. E. Catalytic combustion of diesel soot on Co,K/MgO catalysts. Effect of the potassium loading on activity and stability. Appl. Catal., B 1999, 20, 165–177.
(2) Meher, S. K.; Rao, G. R. Tuning, via counter anions, the morphology and catalytic activity of CeO2 prepared under mild conditions. J. Colloid Interface Sci. 2012, 373, 46–56.
(3) Rao, G. R.; Kašpar, J.; Meriani, S.; di Monte, R.; Graziani, M. NO Decomposition over partially reduced metalized CeO2-ZrO2 solid solutions. Catal. Lett. 1994, 24, 107–112.
(4) Nascimento, L. F.; Serra, O. A. Washcoating of cordierite honeycomb with ceria-copper mixed oxides for catalytic diesel soot combustion. Process Saf. Environ. Prot. 2016, 101, 134–143.
(5) Fornasiero, P.; Dimonte, R.; Rao, G. R.; Kašpar, J.; Meriani, S.; Trovarelli, A.; Graziani, M. Rh-loaded CeO2-ZrO2 solid solutions as highly efficient oxygen exchangers: dependence of the reduction behavior and the oxygen storage capacity on the structural-properties. J. Catal. 1995, 151, 168–177.
(6) Bensaid, S.; Russo, N.; Fino, D. CeO2 Catalysts with fibrous morphology for soot oxidation: the importance of the soot–catalyst contact conditions. Catal. Today 2013, 216, 57–63.
(7) Oliveira, C. F.; Garcia, F. A. C.; Aratuí, D. R.; Macedo, J. L.; Dias, S. C. L.; Dias, J. A. Effects of preparation and structure of cerium-zirconium mixed oxides on diesel soot catalytic combustion. Appl. Catal., A 2012, 413–414, 292–300.
(8) Giménez-Mañogil, J.; Bueno-López, A.; García-García, A. Preparation, characterisation and testing of CuO/Ce0.8Zr0.2O2 catalysts for NO oxidation to NO2 and mild temperature diesel soot combustion. Appl. Catal., B 2014, 152–153, 99–107.
(9) Hernández-Giménez, A. M.; dos Santos Xavier, L. P.; Bueno-López, A. Improving ceria-zirconia soot combustion catalysts by neodymium doping. Appl. Catal., A 2013, 462–463, 100–106.
(10) Wei, Y.; Liu, J.; Zhao, Z.; Duan, A.; Jiang, G. The catalysts of three-dimensionally ordered macroporous Ce1−xZrxO2-supported gold nanoparticles for soot combustion: the metal–support interaction. J. Catal. 2012, 287, 13–29.
(11) Aneggi, E.; de Leitenburg, C.; Trovarelli, A. On the role of lattice/surface oxygen in ceria–zirconia catalysts for diesel soot combustion. Catal. Today 2012, 181, 108–115.
(12) Alinezhadchamazketi, A.; Khodadadi, A. A.; Mortazavi, Y.; Nemati, A. Catalytic Evaluation of promoted CeO2-ZrO2 by transition, alkali, and alkaline-earth metal oxides for diesel soot oxidation. J. Environ. Sci. 2013, 25, 2498–2506.
(13) Miceli, P.; Bensaid, S.; Russo, N.; Fino, D. Effect of the morphological and surface properties of CeO2-based catalysts on the soot oxidation activity. Chem. Eng. J. 2015, 278, 190–198.
(14) Neef, J. P. A.; Makkee, M.; Moulijn, J. A. Metal oxides as catalysts for the oxidation of soot. Chem. Eng. J. 1996, 64, 295–302.
(15) Jelles, S. J.; van Setten, B. A. A. L.; Makkee, M.; Moulijn, J. A. Molten salts as promising catalysts for oxidation of diesel soot: importance of experimental conditions in testing procedures. Appl. Catal., B 1999, 21, 35–49.
(16) Courcot, D.; Pruvost, C.; Zhlininskaya, E. A.; Aboukaïs, A. Potential of supported copper and potassium oxide catalysts in the combustion of carbonaceous particles. Kinet. Catal. 2004, 45, 580–588.
(17) Castoldi, L.; Matarrere, R.; Lietti, L.; Forzatti, P. Intrinsic reactivity of alkaline and alkaline-earth metal oxide catalysts for oxidation of soot. Appl. Catal., B 2009, 90, 278–285.
(18) Assiat, A.; Siffert, S.; Courcot, D. Investigation of Cs–Cu/ZrO2 systems for simultaneous NOX reduction and carbonaceous particles oxidation. Catal. Today 2012, 191, 90–95.
(19) Assiat, A.; Siffert, S.; Courcot, D.; Cousin, R.; Aboukaïs, A. VOCs and carbonaceous particles removal assisted by NOx on AlK2.15/ZrO2 and Cs8–M6/ZrO2 catalysts (M=Cu or Co). C. R. Chem. 2010, 13, 515–526.
(20) Ito, K.; Kishikawa, K.; Watajima, A.; Ikeue, K.; Machida, M. Soot combustion activity of NO3-sorbing Cs–MnOx–CeO2 catalysts. Catal. Commun. 2007, 8, 2176–2180.