**Article**

**Pd₄S/SiO₂: A Sulfur-Tolerant Palladium Catalyst for Catalytic Complete Oxidation of Methane**

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**Abstract:** Sulfur species (e.g., H₂S or SO₂) are the natural enemies of most metal catalysts, especially palladium catalysts. The previously reported methods of improving sulfur-tolerance were to effectively defer the deactivation of palladium catalysts, but could not prevent PdO and carrier interaction between sulfur species. In this report, novel sulfur-tolerant SiO₂ supported Pd₄S catalysts (5 wt. % Pd loading) were prepared by H₂S–H₂ aqueous bubble method and applied to catalytic complete oxidation of methane. The catalysts were characterization by X-ray diffraction, Transmission electron microscopy, X-ray photoelectron Spectroscopy, temperature-programmed oxidation, and temperature-programmed desorption techniques under identical conditions. The structural characterization revealed that Pd₄S and metallic Pd⁰ were found on the surface of freshly prepared catalysts. However, Pd₄S remained stable while most of metallic Pd⁰ was converted to PdO during the oxidation reaction. When coexisting with PdO, Pd₄S not only protected PdO from sulfur poisoning, but also determined the catalytic activity. Moreover, the content of Pd₄S could be adjusted by changing H₂S concentration of H₂S–H₂ mixture. When H₂S concentration was 7 %, the Pd₄S/SiO₂ catalyst was effective in converting 96% of methane at the 400 °C and also exhibited long-term stability in the presence of 200 ppm H₂S. A Pd₄S/SiO₂ catalyst that possesses excellent sulfur-tolerance, oxidation stability, and catalytic activity has been developed for catalytic complete oxidation of methane.

**Keywords:** sulfur-tolerance; Pd₄S; catalytic oxidation of methane; sulfur poisoning

1. Introduction

Methane as the main component of natural gas is playing an increasingly important role in the global energy structure [1,2]. Effective catalytic complete oxidation of CH₄ can improve combustion efficiency and reduce air pollutants, such as CO, NOₓ, and unburned hydrocarbon [3–8]. It has therefore found great applications in modern industry, such as catalytic exhaust converters aimed to reduce methane emission and catalytic gas turbine combustors designed to combust fuel under mild conditions [9,10]. Supported PdO catalysts have shown excellent catalytic property in methane oxidation, and currently are under extensive study [11–18]. However, once sulfur species (e.g., H₂S or SO₂) are present in the reaction atmosphere, the poisoning of PdO catalyst which would lead to inactive PdO-SOₓ is irreversible and the activity of the catalyst cannot be recovered at relatively low temperature [19–25].

Hence, many efforts have been devoted in the past decade to enhance sulfur resistance of supported PdO catalysts. Currently there are two primary approaches to improve the performance of palladium...
catalysts against sulfur poisoning: the first is to use alkaline carriers (e.g., γ-Al₂O₃) and enhance their adsorption ability toward acidic sulfur species to protect the active phase of PdO [23,26,27], and the second is to introduce an extra active ingredient to form a catalyst system with dual activity, such as Pd–Pt complex, to avoid sulfur poisoning [24,28]. However, these methods can only defer the deactivation of palladium catalysts as neither the alkaline carrier nor the extra active ingredient can prevent the interaction between PdO and sulfur species. In other words, sulfur poisons would eventually encroach PdO and make it inactive. As such, these catalyst systems did not really possess the ability of sulfur-tolerance.

The research on sulfur-tolerant palladium catalyst system in methane catalytic oxidation reaction is rare and lack of substantial progress in the literature [20,26–28]. Therefore, development of a reliable sulfur-tolerant catalyst system seems to be of great importance. In view of the great potential of catalytic oxidation of methane, we decided to pursue a new catalytic system that could be of high tolerance of sulfur poisons. We speculated PdₓSₙ in combination with acidic carrier would be an ideal system for methane oxidation based on the following two points. First, it would be the best scenario for sulfur-tolerant catalysts that neither the support nor the palladium active phase itself could interact with sulfur species. PdₓSₙ and acidic carrier such as SiO₂ would likely meet the requirement. Second, seeing that sulfur and oxygen are located in the adjacent position of the same main group in the periodic table, i.e., the chalcogen group, the designed PdₓSₙ might possess similar catalytic activity to PdO.

In the literature, the majority of PdₓSₙ (Pd₄S, Pd₃S, Pd₂S, Pd₁.₈S, PdS or PdS₂, etc.) were prepared by gas sulfuration with H₂S–H₂ atmosphere [25,29–35]. Herein, we would like to present a new procedure for the preparation of PdₓSₙ/SiO₂ catalysts via aqueous bubble sulfuration of Pd/SiO₂ with H₂S–H₂ with varied H₂S concentration. Compared with the gas sulfuration, the aqueous bubble method was performed in much milder conditions. Besides the sulfur resistance and catalytic activity, the stability of PdₓSₙ/SiO₂ catalyst was the other focus of our investigation.

2. Results and Discussion

2.1. Fresh Catalysts

2.1.1. Catalyst Characterization

Freshly prepared catalysts were first tested by X-ray diffraction (XRD) as showed in Figure 1. The freshly prepared catalyst is named (fV), where V represents H₂S concentration. No other palladium species were found except for metallic Pd⁰. The sulfuration of Pd to form Pd₄S under H₂S–H₂ atmosphere was via the reaction: 4Pd + H₂S ⇌ Pd₄S + H₂ [36–40]. This reversible reaction meant that metallic Pd⁰ could not be fully sulfurized to Pd₄S. Therefore, it was reasonable to detect metallic Pd⁰ on the surface of freshly sulfurized catalyst. However, it was worth noting that the intensity of the diffraction peak of metallic Pd⁰ changed regularly with the increase of H₂S concentration. The average particle size of metallic Pd⁰ calculated by Scherrer formula was further shown in Table 1. With the increase of H₂S concentration, the change of average particle size of metallic Pd⁰ could be divided into three stages. They were gradually reduced (0 → 5%), stable (5% → 7%), and increased (7% → 10%). These results indicated the Pd/SiO₂ precursor had been changed by sulfuration.
were further analyzed to provide Table 2 that listed the composition ratio of palladium species of freshly prepared catalysts. These results are in good agreement with the characterization results of XRD and HR-TEM. If the Pd4S had similar properties to PdO, the amount of Pd4S would be the key factor influencing the performance of the catalyst. The XPS data (Figure 3) could provide further evidence for the existence of Pd4S under H2S-H2 atmosphere showed that the Pd4S with the highest proportion of Pd/S was the first Pd3Sy species [38,41]. Therefore, it was reasonable to firstly form the Pd4S under the condition of 60 °C aqueous bubble sulfuration.

The subsequent characterization by X-ray photoelectron spectroscopy (XPS) could provide further evidence for the existence of Pd3Sy, the freshly prepared catalysts were further characterized by high resolution transmission electron microscopy (HR-TEM) and illustrated in Figure 2. The lattice spacing distance of Pd species particles on freshly prepared catalyst are 0.225 nm and 0.245 nm, corresponding to the Pd(111) and Pd4S(102), respectively [JCPDS No. 73-1387, JCPDS No. 46-1043]. In addition to the metallic Pd(111), the Pd4S(102) was found on the surface of all the freshly prepared catalysts. The literature on the preparation of Pd3Sy under H2S-H2 atmosphere showed that the Pd4S with the highest proportion of Pd/S was the first Pd3Sy species [38,41]. Therefore, it was reasonable to firstly form the Pd4S under the condition of 60 °C aqueous bubble sulfuration.

Since XRD characterization could not directly provide evidence of the existence of Pd3Sy, the freshly prepared catalysts were further characterized by high-resolution transmission electron microscopy (HR-TEM) and illustrated in Figure 2. The lattice spacing distance of Pd species particles on freshly prepared catalyst are 0.225 nm and 0.245 nm, corresponding to the Pd(111) and Pd4S(102), respectively [JCPDS No. 73-1387, JCPDS No. 46-1043]. In addition to the metallic Pd(111), the Pd4S(102) was found on the surface of all the freshly prepared catalysts. The literature on the preparation of Pd3Sy under H2S-H2 atmosphere showed that the Pd4S with the highest proportion of Pd/S was the first Pd3Sy species [38,41]. Therefore, it was reasonable to firstly form the Pd4S under the condition of 60 °C aqueous bubble sulfuration.

The subsequent characterization by X-ray photoelectron spectroscopy (XPS) could provide further evidence for the existence of Pd3Sy, as shown in Figure 3. After curve fitting analysis, the S2p3/2 of freshly prepared catalyst could be deconvoluted into two peaks at ~335.6 eV and ~337.5 eV which corresponded to S0 [42] and Pd4S [42–44], respectively. With the increase of H2S concentration, the XPS peak intensity of sulfur species increased gradually. At the same time, the Pd3d5/2 could be deconvoluted into two peaks at ~335.6 eV and ~337.5 eV which corresponded to metallic Pd0 [45,46] and Pd4S [47,48], respectively. This indicated that Pd4S and metallic Pd0 were the primary palladium species on the freshly prepared catalysts. These results are in good agreement with the characterization results of XRD and HR-TEM. If the Pd4S had similar properties to PdO, the amount of Pd4S would be the key factor influencing the performance of the catalyst. The XPS data (Figure 3) were further analyzed to provide Table 2 that listed the composition ratio of palladium species of freshly prepared catalysts. It could be noted that the sulfuration process was the transition of metallic Pd0 to Pd4S. With the increase of H2S concentration, the change of Pd4S ratio could also be divided into

![X-ray diffraction (XRD) patterns of freshly prepared catalysts sulfurized with different H2S concentration.](image-url)

**Table 1.** Average particles size of freshly prepared catalysts sulfurized with different H2S concentration.

| Catalyst | FWHM  | Size (nm) |
|----------|-------|-----------|
| Pd       | 0.761 | 12.2      |
| f0.2     | 0.803 | 11.5      |
| f1       | 1.328 | 6.9       |
| f3       | 1.297 | 6.7       |
| f5       | 3.329 | 2.6       |
| f7       | 3.262 | 2.6       |
| f10      | 2.163 | 4.0       |

FWHM: full-width at half-maximum
three stages. They were gradually increased (0 → 5%), stable (5% → 7%), and reduced (7% → 10%). Variation of metallic Pd\(^0\) content was opposite to that of Pd\(_4\)S. This variation was entirely consistent with the average particle size of metallic Pd\(^0\). It was obvious that the variation of the average particle size of metallic Pd\(^0\) was caused by the change of metallic Pd\(^0\) content on the catalyst surface.

*Figure 2.* High resolution transmission electron microscopy (HR-TEM) images of freshly prepared catalysts with different H\(_2\)S concentration.
2.1.2. Activity Studies

In order to test whether the Pd$_4$S possessed the desired sulfur-tolerance and catalytic activity, its catalytic property for methane oxidation in the presence of 200 ppm H$_2$S was then examined by measuring methane conversion against the reaction time at different reaction temperatures. As shown in Figure 4, when the temperature was 500 °C, the presence of H$_2$S had no impact on all the catalysts. However, once the reaction temperature dropped to 400 °C, the compared PdO/SiO$_2$ catalyst was deactivated very rapidly. We estimate that at this temperature sulfur species could...
deactivated very rapidly. We estimated that at this temperature sulfur species could turn the active PdO into inactive PdO–SOx species, which could then hardly decompose at low temperature [23,24,49]. In contrast, under the same conditions, all the catalysts prepared by our own procedure did not show any deactivation at 400 °C. This clearly stated that the combination of Pd4S and SiO2 was effective in resisting sulfur poisoning. At the same time, the activity of the catalyst with 7% H2S concentration was even equal to that of PdO catalyst. This further stated that the combination of Pd4S and SiO2 had high enough catalytic activity. Furthermore, it was found that the methane conversion of all catalysts decreased to less than 10% at 370 °C. This dramatic decrease in catalytic activity was not due to sulfur poisoning, but the high reaction temperature required for methane activation [50–52]. Therefore, it was best to set the reaction temperature at 400 °C. This temperature could not only reflect the sulfur-tolerance, but also compare the catalytic activity.

![Figure 4](image_url)  
**Figure 4.** Catalytic performance of freshly prepared catalysts with different H2S concentration. Gas composition: CH4 (v% = 2%), O2 (v% = 8%), H2S (v% = 0.02%), and N2 (v% = 89.8%); Flow rate = 200 mL/min; and GHSV (gas hourly space velocity) = 60000 mL/(g·h).

Meanwhile, it should be pointed out here that although all the sulfurized catalysts exhibited the similar sulfur-tolerance, the catalytic activity at 400 °C was not same. As the H2S concentration increased from 0.2% to 7%, the catalytic activity increased gradually. However, when the H2S concentration increased to 10%, the catalytic activity decreased. This variation was very similar to the variation of Pd4S content on the surface of freshly prepared catalyst. However, we could not simply assume that catalytic activity depended solely on Pd4S. The reason was that the stability of Pd4S and metallic Pd0 on the surface of freshly prepared catalyst was still undiscovered under high reaction temperature and presence of oxygen. Under such reaction condition, metallic Pd0 was liable to be oxidized to PdO. Therefore, palladium species on the surface of freshly prepared catalyst might not be the true palladium species involved in the reaction. Next, we would characterize the used catalyst to determine the actual palladium species on the catalyst surface.

2.2. Used Catalyst

2.2.1. Catalyst Characterization

The XRD patterns of used catalysts were given in Figure 5. The used catalyst is named (uV), where V represents H2S concentration. The characteristic diffraction peak attributed to sulfur species was found on the compared PdO/SiO2 catalyst. However, no diffraction peaks attributed to sulfur species were found in all sulfurized catalysts after the reaction. The reason should be that the sulfurized catalyst had the ability to resist sulfur poisoning. Not surprisingly, almost all the diffraction peaks observed in the sulfurized catalyst were attributed to PdO after the reaction. A weak diffraction peak of metallic Pd0 could be observed only when H2S concentration was 0.2%. This implied that most of
the metallic Pd\textsuperscript{0} on the freshly prepared catalyst had been oxidized to PdO under reaction conditions. However, the above results did not show whether the most important Pd\textsubscript{4}S remains stable during the reaction and this needed to be identified by other characterization.

![HR-TEM images of the used catalysts](image)

**Figure 5.** XRD patterns of used catalysts with different H\textsubscript{2}S concentration.

The presence of PdO confirmed our previous speculation that the palladium species on the surface of freshly prepared catalysts were not entirely stable during the vigorous oxidation reaction. However, XRD characterization could only reveal that PdO species were formed during the reaction of freshly prepared catalysts. However, whether the essential Pd\textsubscript{4}S species could stably exist in large quantities would be the main factor affecting the sulfur-tolerance of the catalyst. Figure 6 shows HR-TEM images of the used catalysts. It could be found that the palladium species on the surface of the used catalyst were more complicated than the freshly prepared catalyst. Figure 6 clearly indicates that in addition to Pd\textsuperscript{0}(111), PdO(101) and PdO(110) also appeared in large numbers on the surface of all the used catalysts [JCPDS No.06-0515]. At the same time, the most interesting thing was that Pd\textsubscript{4}S(102) species could be found on all catalyst surfaces. This indicated that the Pd\textsubscript{4}S species could remain stable during the high temperature and high oxygen reaction of methane oxidation.
Figure 6. HR-TEM images of the used catalysts with different H₂S concentration.

Owing to the lack of data on the relative content of PdO on the surface of used catalyst, when Pd₄S and PdO coexist, we could not distinguish whether Pd₄S and PdO affect the catalytic activity alone or in combination. Therefore, used catalysts were further analyzed by XPS characterization, as shown in Figure 7. After curve fitting analysis, the Pd3d₅/₂ could be deconvoluted into three peaks at ~337.5 eV, ~336.9 eV, and ~335.6 eV, which were assigned to Pd₄S [47,48], PdO [48], and metallic Pd⁰ [45,46], respectively. The above characterization results revealed the fact that under the reaction conditions, the actual palladium species on the used catalyst surface should be Pd₄S, PdO, and metal Pd⁰. At the same time, the S2p peak attributed to S⁰ was not observed (see Figure 3), only the very weak S2p peak attributed to Pd₄S could be observed. In contrast, the Pd3d peak at ~337.3 eV and S2p peak at 168.1 eV of used PdO/SiO₂ could be attributed to PdO-SOₓ. This comparison results indicated that Pd₄S could protect other palladium species from sulfur poisoning.
Figure 7. XPS Pd\textit{3d} and S\textit{2p} of the used catalysts with different H\textsubscript{2}S concentration.

Table 3 listed the composition ratio of palladium species of used catalysts. Compared with the relative content of palladium species on the surface of fresh catalyst (Table 1), it could be noted that a large number of PdO species appeared on the surface of the used catalyst, while the Pd\textsuperscript{0} content of the metal decreased significantly. This was clearly the oxidation of metal Pd\textsuperscript{0} to PdO during the reaction. At the same time, the relative content of Pd\textsubscript{4}S was basically stable during the reaction. This indicated that the PdO formed during the reaction was mainly derived from the metal Pd\textsuperscript{0}, but not derived from Pd\textsubscript{4}S. Temperature-programmed Oxidation (TPO) of fresh Pd/SiO\textsubscript{2}, f7 and u7 catalysts with the same mass was investigated by thermogravimetric analysis. The oxidation stability of the catalyst was examined by recording the mass change in the process of air oxidation. The results are presented in Figure 8. Three samples had a similar dehydration process before 100 °C. However, with the increase of temperature, the three samples showed completely different changes. Freshly prepared Pd/SiO\textsubscript{2} had the greatest mass increase, which should be related to the oxidation of metallic Pd\textsuperscript{0} to PdO. The mass
increase of f7 with the same mass was significantly smaller than that of freshly prepared Pd/SiO2, while u7 with the same mass had no significant mass increase. f7 was composed of metallic Pd⁰ and Pd₄S, while u7 was mainly composed of PdO and Pd₄S. This stated that the mass increase of f7 was mainly related to the oxidation of metallic Pd⁰, while Pd₄S maintained sufficient oxidation stability even under temperature higher than 500 °C. This meant that Pd₄S could not be oxidized into palladium oxide nor into palladium sulfate. Therefore, it could be possible to conclude that in the low-temperature catalytic oxidation of methane, Pd₄S had sufficient stability to resist the oxidation of oxygen.

Table 3. Palladium species content of used catalysts with different H₂S concentration.

| Catalyst | Composition Ratio of Palladium Species (%) |
|----------|------------------------------------------|
|          | Pd  | PdO | Pd₄S |
| u0.2     | 5.3 | 59.5 | 35.2 |
| u1       | 4.0 | 60.4 | 35.6 |
| u3       | 5.9 | 54.2 | 39.9 |
| u5       | 2.7 | 40.4 | 56.9 |
| u7       | 3.1 | 36.6 | 60.3 |
| u10      | 3.6 | 48.9 | 47.5 |

a: Calculated by Pd fitted peak area by XPS.

Figure 8. Temperature-programmed Oxidation (TPO) profiles of the (u7, f7) catalyst and freshly prepared Pd/SiO₂.

2.2.2. Activity Studies

Figure 9 covered the evaluation of the used catalysts and the evaluation method was completely consistent with the freshly prepared catalysts. To our delight, the sulfur-tolerance and catalytic activity of each used catalyst was almost unchanged with the fresh catalyst at 400 °C, which indicated that the composition of the catalyst had remained stable after the initial evaluation. The previous characterization results had confirmed that Pd₄S, PdO, and metal Pd⁰ were the three palladium species actually involved in the reaction. In the case that PdO and metal Pd⁰ did not have sulfur-tolerance, it was the existence of Pd₄S that gave the palladium active component the ability to resist the poisoning of sulfur species. Moreover, to our surprise, Pd₄S was not merely resistant to sulfur itself, its presence could even protect PdO and metal Pd⁰ from the poisoning of sulfur species.
The sulfur-tolerance of the catalyst depended on Pd₄S, but it remained to be confirmed if catalytic activity was related to the type of palladium species. To this end, we correlated the relative amounts of Pd₄S and PdO species on the used catalyst surface with the catalytic activity of the used catalyst. The secondary reaction performance of the catalyst was selected at 400 °C and the results are shown in Figure 10. It could be noted that the variation of catalytic activity at 400 °C was closely related to the change of Pd₄S content with H₂S concentration increase. As the H₂S concentration increased from 0.2% to 7%, the relative content of Pd₄S and the catalytic activity of the used catalyst gradually increased. Compared with content change of (Pd₄S + PdO) and PdO, the content of (Pd₄S + PdO) did not change with the concentration of H₂S, but the change of PdO content was opposite to the catalytic activity of the used catalyst. The above results showed clearly that not only the sulfur-tolerance, but also the catalytic activity relied completely on Pd₄S. Because the coexistence of PdO did not play any decisive role, it was completely reasonable to use Pd₄S/SiO₂ as the catalyst prepared by the aqueous bubble sulfuration method. The consequences of 72-hour stability test of the u7 catalyst with and without H₂S are shown Figure 11. It could be found that the catalyst could maintain long-term stability regardless of the presence of H₂S in the reaction atmosphere.

![Figure 9](image_url)  
Figure 9. Catalytic performance of used catalysts with different H₂S concentration. Gas composition: CH₄ (v% = 2%), O₂ (v% = 8%), H₂S (v% = 0.02%), and N₂ (v% = 89.8%); Flow rate: 200 mL/min; and GHSV = 60000 ml/(g·h).

![Figure 10](image_url)  
Figure 10. Relationship profile between composition ratio of Pd₄S and PdO on used catalysts and second evaluation of methane conversion. The composition ratio of palladium species was calculated through Pd fitted peak area by XPS.
products were barely detected from the u7 catalyst. Seeing that Pd prepared PdO
the two catalysts, i.e., the presence of Pd PdO–SO
SO
SO
2.3. Mechanism of Sulfur-Tolerance

PdO) did not change with the concentration of H 2S, but the change of PdO content was opposite to
Figure 12. SO 2 and H 2S were the primary desorption species detected in the study. The PdO/SiO 2
catalyst. The secondary reaction performance of the catalyst was selected at 400 °C and the results
related to the change of Pd 4S content with H 2S concentration increase. As the H 2S concentration
increased from 0.2% to 7%, the relative content of Pd 4S and the catalytic activity of the used catalyst
maintain long-term stability regardless of the presence of H2S in the reaction atmosphere.

gradually increased. Compared with content change of (Pd4S + PdO) and PdO, the content of (Pd4S +
amounts of Pd4S and PdO species on the used catalyst surface with the catalytic activity of the used
catalyst. The reason is that Pd 4S can resist the poisoning of sulfur species. Moreover, to our surprise, Pd 4S
is not merely resistant to sulfur itself, its presence could even protect PdO and metal Pd0 from the poisoning of sulfur species.

Pd 4S was the sulfur-tolerance, but also the catalytic activity relied completely on Pd 4S. Because the coexistence of
PdO did not play any decisive role, it was completely reasonable to use Pd 4S/SiO2 as the catalyst
contrast, desorption products were barely detected from the u7 catalyst. Seeing that Pd 4S was the

Scheme 1. Aside from not adsorbing H 2S, Pd4S also prevented PdO from adsorbing H 2S

Next, we turned to investigate the cause of sulfur-tolerance of the Pd 4S/SiO 2 using the technique
of hydrogen sulfide temperature-programmed desorption (H 2S-TPD). The u7 catalyst and the freshly
prepared PdO/SiO 2 catalyst were chosen for comparison and the results are presented in Figure 12.
SO 2 and H 2S were the primary desorption species detected in the study. The PdO/SiO 2 catalyst released
SO 2 in relatively large quantity, which suggested that PdO could readily assimilate H 2S to form
PdO–SO X. As a result, PdO/SiO 2 catalyst was poisoned and deactivated by H 2S. In contrast, desorption
products were barely detected from the u7 catalyst. Seeing that Pd4S was the only discrepancy between
the two catalysts, i.e., the presence of Pd4S in u7 and its absence in PdO/SiO2, we were convinced that
Pd4S played a vital role in the sulfur-tolerance of u7 catalyst, as depicted in Scheme 1. Aside from not
adsorbing H2S, Pd4S also prevented PdO from adsorbing H2S onto its surface. Therefore, it was the
Pd4S that blocked the adsorption of H2S and endowed the catalyst with sulfur-tolerance.

Figure 11. Long-term stability test of the u7 catalyst with and without H 2S. Gas composition:
CH 4 (v% = 2%), O 2 (v% = 8%), H 2S (v% = 0.02%), and N 2 (v% = 89.8%); Flow rate: 200 mL/min;
and GHSV = 60000 mL/(g·h).

2.3. Mechanism of Sulfur-Tolerance

Figure 12. Hydrogen sulfide temperature-programmed desorption (H 2S-TPD) profiles of the u7 catalyst
and freshly prepared PdO/SiO2 catalyst.
After subtraction of the Shirley-type background, the core-level spectra were decomposed into their component with mixed Gaussian-Lorentzian lines by a non-linear least squares curve fitting procedure, using the public software package XPSPEAK4.1. The corresponding atomic ratio in different chemical fractions peak.

Scheme 1. Schematic diagram of methane catalytic oxidation on the surface of Pd₄S/SiO₂ and PdO/SiO₂ in presence of H₂S.

3. Materials and Methods

3.1. Catalyst Preparation

The PdO/SiO₂ catalyst was prepared by isovolumetric impregnation. Typically, weigh a proper quantity of 40–60 mesh SiO₂ (M = 10 g Vg = 0.94 cm³/g, Rg = 10.6 nm, S = 353.0028 m²/g, Qingdao Baisha Catalyst Factory, Qingdao, China) dispersed in palladium acetate (Aladdin Industrial Corporation, Shanghai, China) aqueous solution (Vpd = 0.05 g/mL) overnight. Then the sample was dried in an oven at 110 °C for 4 h and calcined at 500 °C for 4 h in the air. The theoretical loading of Pd was 5 wt. %.

The PdO/SiO₂ was first reduced to Pd/SiO₂ by H₂ at 500 °C for 1 h. Pd₄Sₓ/SiO₂ catalyst was prepared by using above Pd/SiO₂ as precursor. 2.0 g Pd/SiO₂ and 100 ml deionized water were stirred at 350 rpm in a three-necked flask. Adjust the flow rate of H₂S and H₂ by flow controller (D07-19B, Beijing Sevenstart Electronics Co. Ltd, Beijing, China) to configure different concentrations of H₂S/H₂ mixture. Then 30 mL/min of H₂S–H₂ (VH₂S%= 0.2, 1, 3, 5, 7, 10) was fed into the suspension at 60 °C for 1 h. Afterwards, the sample was filtered and rinsed with distilled water till neutral. Finally, the sample was dried at 110 °C for 4 h. The freshly prepared catalyst is named (fV), and the used catalyst is named (uV), where V represents H₂S concentration.

3.2. Catalyst Characterization

X-Ray Diffraction (XRD) was carried out on a Thermo ARL X'TRA diffractometer (PNAlytical Co. Holland) using Cu K-α radiation (45 kV, 40 mA). Average particle size was determined from XRD measurements using the Scherrer formula:

\[
d = \frac{K\lambda}{\beta \cos \theta},
\]

where d is the average particle size (nm), K is the Scherrer constant and the diffraction angle is denoted θ, \( \lambda = 0.154 \text{ nm} \) stands for the wavelength of Cu K-α radiation, \( \beta \) denotes the full-width at half-maximum (FWHM) of diffraction peak.

High Resolution Transmission Electron Microscopy (HR-TEM) images were taken by a Philips-FEI Tecnai G2 F30 S-Twin transmission electron microscope operated at 300 kV (Philips- FEI Co. Holland). X-Ray Photoelectron Spectroscopy (XPS) was measured on a Thermo ESCALAB 250 Axis Ultra (KRATOS, Kanagawa, Japan) using a monochromated Al Kα X-ray source (hv = 1485.6 eV) with a fixed analyzer pass energy of 80 eV. The binding energy values were referenced to the Si 2p as internal standard (Si 2p = 103.4 eV) and the maximum deviation value was 2.6 eV in the sample. After subtraction of the Shirley-type background, the core-level spectra were decomposed into their component with mixed Gaussian-Lorentzian lines by a non-linear least squares curve fitting procedure, using the public software package XPSPEAK4.1. The corresponding atomic ratio in different chemical
environment was obtained from the fitted XPS spectra of Pd 3d and S 2p. The XPS profiles were fitted by the software named “XPS peak”. Then the fitting peak area was used to calculate the proportion of different species.

Temperature-programmed Oxidation (TPO) was performed on a NETZSCH STA 409 PC/PG instrument (NETZSCH Co. Selbc, Germany). The oxidation stability of the catalysts was investigated by recording the mass change in the process of air oxidation. TPO was performed by heating 0.01 g sample from room temperature to 600 °C in air atmosphere with a heating rate of 5 °C/min and a flow rate of 40 mL/min.

Temperature-programmed Desorption (TPD) of hydrogen sulfide experiments were performed in a self-made tubular quartz reactor (5mm i.d.). The sample (0.2 g) was first swept at 110 °C for 1 h using pure He and cooled to room temperature in the same atmosphere. Then the sample was in situ treated with H2S (0.2% in N2) at a flow rate of 30 mL/min for 0.5 h and swept 1 h to remove physisorbed and/or weakly bound species. TPD was performed by heating the sample from room temperature to 800 °C with constant increase of 5 °C/min in pure He. The TPD spectra were recorded by a quadrupole mass spectrometer (QMS 200 Omnistar, Pfeiffer Co. Germany).

3.3. Evaluation of Catalysts

The catalytic activity of the freshly prepared and used catalysts was tested with 0.2 g sample in a self-made continuous fixed bed reactor (8 mm i.d.) at atmospheric pressure. Gases consisting of CH4 (v% = 2 %), O2 (v% = 8 %), H2S (v% = 0.02 %), and N2 were fed through the flow controller (D07-19B, Beijing Sevenstart Electronics Co. Ltd., Beijing, China) at 200 mL/min and used in all the experiments. Finally, the temperature control controller (AI808PK1L2, XiaMen YuDian Automation Technology Co., Ltd., Xiamen, China) is used to control different reaction temperatures. The effluent gases were sampled and simultaneously analyzed online by gas chromatographs (GC-9790, Zhejiang Fuli Analytical Instruments Corp., Hangzhou, China). Exhaust gases were analyzed using a PoraPak Q column and a thermal conductivity detector (TCD). Methane conversions were calculated for outlet CO2 concentrations.

4. Conclusions

Through the characterization of freshly prepared catalyst and used catalyst, we confirmed that Pd4S, PdO, and metallic Pd0 were the actual palladium species involved in the oxidation of methane. Sulfur-tolerance and catalytic activity was completely dependent on Pd4S, and independent on other palladium species. Moreover, Pd4S had sufficient oxidation stability under reaction conditions. Therefore, even in the presence of PdO, there are enough reasons to represent the catalyst with Pd4S/SiO2. In summary, we have developed a powerful sulfur-tolerant catalyst for methane oxidation by incorporating Pd4S into SiO2, and to the best of our knowledge, this is the first report on Pd catalysts with such property. In view of the excellent sulfur-tolerant property, the excellent oxidation stability and the high catalytic activity, the Pd4S/SiO2 catalyst will definitely find valuable and versatile use in catalytic chemistry.

At the same time, as the Pd4Sx species with the highest proportion of Pd/S, we cannot determine whether the outstanding performance of Pd4S in methane catalytic oxidation is only a special case. Furthermore, sulfur-tolerant mechanism of Pd4S needs further theoretical research.

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