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Efficient and reusable ordered mesoporous WO_x/SnO₂ catalyst for oxidative desulfurization of dibenzothiophene†

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The oxidative desulfurization (ODS) of organic sulfur compounds over tungsten oxide supported on highly ordered mesoporous SnO₂ (WO_x/meso-SnO₂) was investigated. A series of WO_x/meso-SnO₂ with WO_x contents from 10 wt% to 30 wt%, were prepared by conventional wet impregnation. The physico-chemical properties of the WO_x/meso-SnO₂ catalysts were characterized by X-ray diffraction (XRD), N₂ adsorption–desorption isotherms, electron microscopy, Fourier transform infrared spectroscopy (FT-IR), Raman spectroscopy, and the temperature-programmed reduction of hydrogen (H₂-TPR). The characterization results indicated that these catalysts possessed mesoporous structures with uniform pores, high specific surface areas, and well-dispersed polyoxotungstate species on the surface of meso-SnO₂ support. The ODS performances were evaluated in a biphasic system (model oil/acetonitrile, S_{initial} = 2000 ppm), using H₂O₂ as an oxidant, and acetonitrile as an extractant. Dibenzothiophene (DBT) in the model oil was removed completely within 60 min at 50 °C using 20 wt% WO_x/meso-SnO₂ catalyst. Additionally, the effect of reaction temperature, H₂O₂/DBT molar ratio, amount of catalyst and different sulfur-containing substrates on the catalytic performances were also investigated in detail. More importantly, the 20 wt% WO_x/meso-SnO₂ catalyst exhibited 100% sulfur-removal efficiency without any regeneration process, even after six times recycling.

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1. Introduction

Sulfur-containing compounds in transportation fuels are converted to SO_x, which is a major source of air pollution and energy corrosion.¹ Thus, removal of sulfur has become an important research subject worldwide, and many countries have legislated environmental regulations that limit sulfur content in fuels to be below 10 ppm.² To date, hydrodesulfurization (HDS) is a conventional desulfurization method in the petroleum refining industry for the removal of sulfur in fuels, including thiols, thioethers, and disulfides. However, the HDS process has some respective disadvantages. For example, HDS requires severe operation conditions at high pressure of (20–100) atm of H₂ and temperatures (300–400 °C).³ Additionally, it is difficult to remove refractory sulfides, such as benzo-*thiophene* (BT), dibenzothiophene (DBT), and their derivatives, owing to their steric hindrance, and low electron density around

sulfur atom.⁴ Therefore, alternative processes have been suggested to overcome these drawbacks. So far, several alternative deep desulfurization technologies, such as adsorption,^{5,6} extraction,^{7,8} bioprocess,^{9,10} oxidation,^{11–13} and photocatalytic oxidation desulfurization^{14,15} have been extensively investigated.

Among these processes, oxidative desulfurization (ODS) combined with extraction process is considered to be one of the most promising processes. It can be operated at atmospheric pressure and low temperature without consuming hydrogen. During this process, organic sulfides can be oxidized into highly polar sulfones and sulfoxides by catalysts with suitable oxidants, and removed by the subsequent extraction process using polar organic solvents. Various oxidants have been used for the oxidation of sulfur compounds, including molecular oxygen,^{16–18} ozone,¹⁹ organic peroxide,²⁰ and hydrogen peroxide (H₂O₂).^{21,22} Among them, H₂O₂ has been extensively used, due to its high activity, high oxidative capacity, and production of only water after the reaction.

In the field of heterogeneous catalysis, it is well-known that group 5 and 6 metals (*e.g.*, Mo, W, V) in high oxidation states can react with hydrogen oxide to produce peroxometallate complexes, which are efficient catalysts for oxidative desulfurization reaction.^{8,23,24} Caero *et al.* examined the ODS of a real diesel fuel on V₂O₅ supported on alumina, silica, niobia, ceria, and titania, and reported that an approximately 99% decrease

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in the initial amount of sulfur.²⁵ Prasad *et al.* reported that MoO₃/Al₂O₃-SiO₂ catalyst had the best catalytic performance for ODS of 4,6-dimethyldibenzothiophene (4,6-DMDBT) with *tert*-butyl hydroperoxide.²⁶ A novel composite catalyst V_o-MoO₂/NC exhibited excellent ODS activity and reusability, which was ascribed essentially to the strong electron-donating effect of NC on V_o-MoO₂.²⁷ Additionally, tungsten-based catalysts have also been extensively studied for ODS reaction in both single and biphasic liquid phase operating systems, due to the tungsten-oxo species on the surface of catalysts as active sites being combined with H₂O₂ to form peroxo-tungsten intermediates (W-O-O-H), contributing to the conversion of DBT to DBTO₂ in the oxidation process.²⁸ In order to improve the activity and stability of catalysts, tungsten species are dispersed on various supports such as W-MCM-41,²⁹ WO₃-SBA-15,³⁰ WO_x/TiO₂,³¹ WO_x-ZrO₂,³² WO₃/MoO₃/Al₂O₃,³³ and Mo/KIT-6-Ti.³⁴

Recently, SnO₂-based heterogeneous catalyst containing tungsten oxide has been reported, exhibiting efficient selective oxidation of amines and sulfides with green oxidant H₂O₂, has been reported.³⁵ Zhang *et al.* have prepared WO₃/SnO₂ composite catalysts by the co-precipitation impregnation method for selective the oxidation of 1,2-benzenedimethanol to phthalide using H₂O₂ as oxidant, suggesting that high dispersion of tungsten species on SnO₂ can improve catalytic activity in reaction.³⁶ Ma *et al.* have found that the SnO₂-WO₃ composite as solid acid catalyst is more effective than pure WO₃ and SnO₂ catalysts in the hydrolysis of dichlorodifluoromethane, due to the strong interaction between WO₃ and SnO₂.³⁷ According to the above reports, SnO₂ will be a good choice as support to disperse WO₃ for ODS reaction.

In the present work, highly ordered mesoporous SnO₂ (meso-SnO₂) was successfully prepared from KIT-6 silica template using a nano-replication method. WO_x species were then highly dispersed on the meso-SnO₂ support by an incipient wet-impregnation method. The Deep desulfurization performance of WO_x/meso-SnO₂ catalysts for fuel oil in a biphasic (model oil/ acetonitrile) system under different reaction conditions was investigated in detail. The WO_x/meso-SnO₂ catalyst with 20 wt% WO_x loading showed excellent catalytic performance in removing DBT, BT, and 4,6-DMDBT, because when WO_x species interacted with SnO₂, a lot of active species (tungsten oxo-species, W=O) were generated. Furthermore, the catalysts with high surface area, large pore size, and 3D pore network are beneficial for the diffusion and transport of reactants and products during ODS reaction. In addition, the reusability and stability of the catalyst were investigated.

2. Experimental

2.1 Synthesis of KIT-6 silica template

The typical synthesis of the mesoporous KIT-6 silica template was similar to the process described in the literature.^{38,39} A triblock copolymer (pluronic P123, EO₂₀PO₇₀EO₂₀, Aldrich) was dissolved in distilled water and *n*-butanol solvent was added to the mixture at room temperature. The solution was vigorously stirred for 6 h to obtain a clear polymer solution. The clear solution was then kept in a water bath at 35 °C for 24 h followed by the addition of

hydrochloric acid (HCl, Samchun) and tetraethylorthosilicate (TEOS, Samchun) with magnetic stirring. The molar composition of the mixture was P123 : BuOH : TEOS : HCl : H₂O = (0.017 : 1.01 : 1.33 : 0.45 : 198). After that, the mixture was kept in an oven at 100 °C for another 24 h. The white precipitates were filtered and washed with distilled water and ethanol to completely remove the block copolymer. Finally, the product was calcinated at 550 °C for 3 h in air.

2.2 Synthesis of ordered mesoporous SnO₂

Ordered mesoporous SnO₂ (meso-SnO₂) material was prepared by a nano-replication method using mesoporous KIT-6 as silica template. The meso-SnO₂ material was synthesized by a solvent-free infiltration method.⁴⁰ Typically, 5.09 g SnCl₂·2H₂O (Aldrich) was melted at 100 °C to liquid states. It was then impregnated into 5.0 g of preheated silica template. The composite materials were shaken for 1 h, and put in an oven at 80 °C overnight, in order to let the precursor spontaneously infiltrate into mesopores of the silica template. The composite material was then calcined at 700 °C for 3 h under static air condition. After that, the silica template was removed from the composite by a wet-etching process using a 20 wt% hydrofluoric acid (HF) solution. The resulting solid product was washed with distilled water and acetone several times, and then dried at 80 °C overnight in an oven.

2.3 Synthesis of WO_x/meso-SnO₂ catalysts

WO_x-Supported catalysts were prepared by an incipient wetness impregnation method. To obtain 20 wt% WO_x/meso-SnO₂, an aqueous solution of (NH₄)₆H₂W₁₂O₄₀·*x*H₂O (0.266 g, Aldrich) was impregnated into 1.0 g of meso-SnO₂. After drying at 80 °C overnight, the obtained product was heated at 400 °C for 3 h under static air condition. WO_x/meso-SnO₂ with (10 and 30) wt% loadings were also prepared through the same method.

2.4 Characterization

The X-ray diffraction (XRD) patterns of these prepared catalysts were obtained from a Rigaku D/MAX-2200 ultima equipped with Cu K α radiation ($\lambda = 1.54 \text{ \AA}$) at 30 kV and 40 mA. N₂ adsorption-desorption isotherms were obtained using a Micromeritics Tristar system at liquid N₂ temperature. Before measurements, samples were degassed at 323 K for 12 h. The Brunauer-Emmett-Teller (BET) and Barrett-Joyner-Halenda (BJH) methods were utilized to calculate the BET surface area and pore size distribution, respectively. Scanning electron microscopy (SEM) image was obtained using a Hitachi UHR S 5500 FE-SEM operated at an accelerating voltage of 15 kV. Transmission electron microscopy (TEM) images were collected using JEOL JEM 3010 at an accelerating voltage of 200 kV. Raman spectra were recorded under ambient conditions at room temperature (RT) using WITEC Alpha300. The excitation line of the laser was at 532 nm. Fourier transform infrared spectroscopy (FT-IR) spectra were measured using KBr wafer technique with Bruker IFS-66 spectrometer. H₂-Temperature programmed reduction (H₂-TPR) was performed in a fixed-bed reactor. Sample (20 mg) was put in a quartz microreactor, and pretreated with He up to



100 °C at a rate of 10 °C min⁻¹ for 1 h for pretreatment. Then 10 vol% H₂ in a He flow of 40 mL min⁻¹ was maintained at RT for 30 min. Finally, the sample was ramped to 900 °C at 10 °C min⁻¹.

2.5 Catalytic performance

Sulfur-containing compound (DBT, BT, or 4,6-DMDBT) was dissolved in *n*-heptane using a corresponding S-content of 2000 ppm as model oil. A typical ODS reaction of model oil was carried out in a 100 mL two-necked flask by adding 0.1 g catalyst, 0.27 mL of 34.5% H₂O₂ aqueous solution, 14 mL of acetonitrile, and 14 mL of the model oil successively into the flask, followed by vigorously mixing with a magnetic stirrer at 50 °C for 2 h under atmospheric pressure. Reaction products (upper oil layer) were analyzed by gas chromatography–flame ionization detector (GC–FID) equipped with a HP-5 capillary column (30 m × 0.32 mm inner diameter × 1.0 μm film thickness).

3. Results and discussion

3.1 Catalyst characterization

Fig. 1 shows the low- and high angle XRD patterns for the KIT-6 template (inset), meso-SnO₂, and WO_x/meso-SnO₂ materials. In the low-angle XRD patterns (Fig. 1A), KIT-6 exhibited typical diffraction peaks (211), (220), and (332), which are characteristic of the cubic *Ia3d* mesostructure. The meso-SnO₂ and WO_x/meso-SnO₂ materials exhibited two narrow and well-defined peaks (110) and (211), indicating the highly ordered mesostructure of all materials. The presence of new diffraction peak (110) around 0.60° indicated that after the silica template etching process the cubic *Ia3d* mesostructure of KIT-6 silica template transformed into tetragonal *I4₁/a* (or lower symmetry).⁴¹ In the wide-angle XRD patterns (Fig. 1B), diffraction peaks of meso-SnO₂ with 2θ/degree values corresponding to (110), (101), (200), (211), (220), (002), (310), (301), (202), and (321) planes exhibited a typical tetragonal phase of SnO₂ (JCPDS 21-1250, *P4₂/mnm*). After loading (10 and 20) wt% WO_x on meso-SnO₂, there was no diffraction line of the tungsten oxide species in wide angle patterns, revealing that the WO_x existed mainly in amorphous phases or particles size was very small, and they were finely dispersed on the meso-SnO₂ support. The Diffraction peaks of crystalline WO₃ appeared when 30 wt% WO_x was loaded on meso-SnO₂, as shown in Fig. 1B. Table 1 summarizes the crystallite sizes of all materials that were calculated using the Debye–Scherrer equation.

Mesostructures of KIT-6, meso-SnO₂, and WO_x/meso-SnO₂ materials were confirmed by N₂ adsorption–desorption measurements (Fig. S1†). As shown in Fig. S1(a) and (c),† all the materials exhibited typical type-IV isotherms with H1 hysteresis loop in the range of $p/p_0 = 0.5$ –1.0, as characteristics of mesoporous materials. The corresponding pore size distribution curve calculated from the adsorption of N₂-sorption isotherm showed that KIT-6 only had one porous structure (Fig. S1(b)†), whereas the meso-SnO₂ and WO_x/meso-SnO₂ materials exhibited dual porous structures (Fig. S1(d)†). The smaller pore sizes

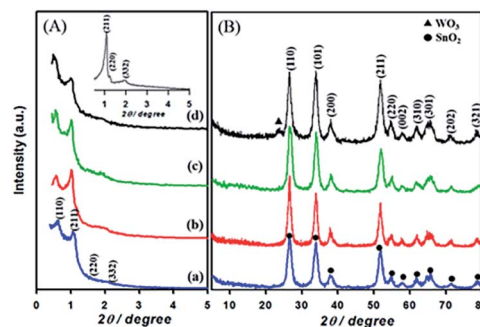


Fig. 1 (A) Low- and (B) high-angle patterns of samples. (a) Meso-SnO₂, (b) 10 wt% WO_x/meso-SnO₂, (c) 20 wt% WO_x/meso-SnO₂, (d) 30 wt% WO_x/meso-SnO₂, and KIT-6 (inset A).

of (2.5–3.3) nm come from the silica wall of the KIT-6 template, while the larger pore sizes (above 10 nm) are caused by the phase-transformation from the cubic *Ia3d* mesostructure to the tetragonal *I4₁/a* (or lower) mesostructure. The surface area, total pore volume, and pore size for KIT-6 were 725 m² g⁻¹, 0.83 cm³ g⁻¹, and 7.0 nm, respectively. Table 1 summarizes the physical properties of meso-SnO₂ and WO_x/meso-SnO₂ materials and shows that after loading different amounts of WO_x on meso-SnO₂ support, the surface areas, pore volumes, and pore sizes of samples were decreased, probably due to the partial pore blockage by the impregnated WO_x. Compared to the recalcinated meso-SnO₂, pure meso-SnO₂ combined with WO_x could suppress the particle agglomeration during the sintering process, due to the cooperative nature of the cations of the mixed oxides.⁴²

The SEM (Fig. 2a–d) and TEM images (Fig. 2e–h) also confirm the meso-SnO₂ and WO_x/meso-SnO₂ materials with regular porosity and well-defined crystalline frameworks. All the materials consisted of well-defined nanopores and frameworks with uniformly repeating units over the whole particle, indicating that the highly ordered mesostructure remained before and after loading works. The W/Sn ratios of the WO_x/meso-SnO₂ materials with different amounts of WO_x loading were obtained by Energy dispersed X-ray spectroscopy (EDX) from SEM analysis (Table 1), indicating that the tungsten content increased with increasing the amount of WO_x loading. High-resolution TEM images (inset of TEM images) indicated that the meso-SnO₂ and (10 and 20) wt% WO_x/meso-SnO₂ materials exhibited well-formed crystalline framework structures. The *d*-spacings of 3.41, 2.68 and 2.35 Å correspond to the (110), (101) and (200) planes of the tetragonal phase of SnO₂, indicating that the WO_x was finely dispersed on the surface of meso-SnO₂, without aggregation. Fig. 2h shows that the catalyst with 30 wt% WO_x loading mainly displayed the crystal SnO₂ structure with tiny WO₃ structure with *d*-spacing of 3.85 Å, which was indexed to the (001) plane of the orthorhombic WO₃ phase.⁴³ EDX mapping images obtained from TEM analysis revealed that the tungsten atoms in WO_x/meso-SnO₂ materials were homogeneously dispersed over the whole particles as shown in Fig. 2j–l.

Fig. 3 shows the Raman spectra of meso-SnO₂ and WO_x/meso-SnO₂ materials in the spectral range of 200 to 1200 cm⁻¹.



Table 1 Physical properties of meso-SnO₂ and X wt% WO_x/meso-SnO₂

Materials	S_{BET}^a (m ² g ⁻¹)	V_{tot}^b (cm ³ g ⁻¹)	D_p^c (nm)	D^d (nm)	W/Sn ^e
Meso-SnO ₂	132	0.41	2.8/20.3	6.9	—
10 wt% WO _x /meso-SnO ₂	90	0.18	2.8/17.0	8.3	9.10
20 wt% WO _x /meso-SnO ₂	78	0.11	2.9/16.4	7.2	19.60
30 wt% WO _x /meso-SnO ₂	57	0.07	2.8/16.5	7.6	27.86
(R) meso-SnO ₂ ^f	73	0.31	3.3/18.0	9.2	—

^a Surface areas were calculated by the BET method from N₂ adsorption isotherms in the range of $p/p_0 = 0.05\text{--}0.20$. ^b Total pore volumes were calculated from the N₂ adsorption data at $p/p_0 = 0.99$. ^c Pore sizes were obtained from the adsorption branches of N₂ sorption isotherms by the BJH method. ^d Crystallite sizes were calculated using Scherrer's equation from the high-angle XRD patterns. ^e Surface Sn/W calculated from the SEM-EDX results. ^f R represents the meso-SnO₂ was re-calculated at 400 °C for 3 h such as WO_x/meso-SnO₂ catalyst.

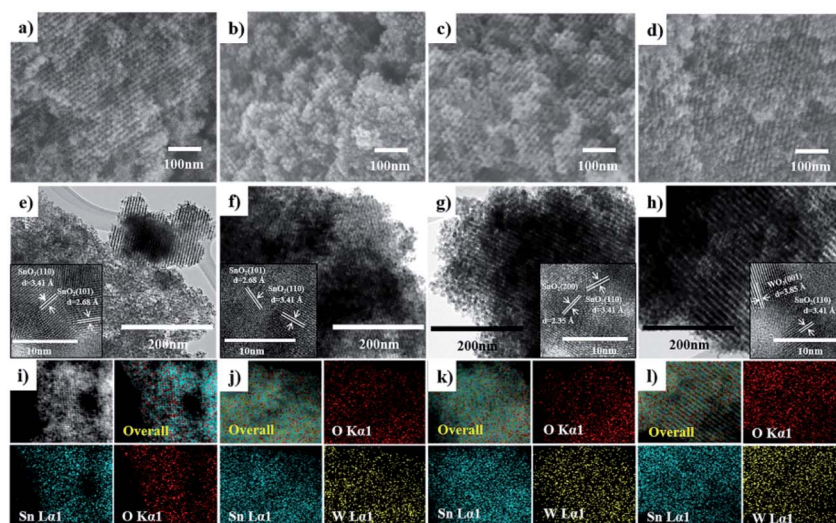


Fig. 2 Electron images of all the prepared materials. (a–d) Representative SEM images, (e–h) representative TEM images with high-resolution TEM images (inset), and (i–l) elemental mapping images of meso-SnO₂, 10 wt% WO_x/meso-SnO₂, 20 wt% WO_x/meso-SnO₂, and 30 wt% WO_x/meso-SnO₂.

The spectrum of meso-SnO₂ showed the bands at around 476 cm⁻¹ (E_g), 633 cm⁻¹ (A_{1g}), and 774 cm⁻¹ (B_{2g}) that could be assigned to the tetragonal structure of SnO₂.⁴⁴ After loading tungsten species, the prominent A_{1g} band was shifted to higher wave numbers than that of pure meso-SnO₂, indicating the presence of interaction between WO_x species and SnO₂.⁴⁵ Simultaneously, the broad band appeared in the 200–400 cm⁻¹ region was attributed to the W–O–W bending modes.⁴⁶ The new band at around 960–980 cm⁻¹ appeared in all the WO_x/meso-SnO₂ materials was attributed to the terminal W=O bonds of surface WO_x species. The shift of surface W=O band from 960 cm⁻¹ to 980 cm⁻¹ with increasing the WO_x loading might be related to the polymerization of surface monooxo tungsten species.⁴⁷ With further increase in WO_x loading (30 wt%), three new bands at about 272 cm⁻¹, 715 cm⁻¹ and 807 cm⁻¹ were observed. This can be assigned to asymmetric and symmetric stretching vibration of W–O–W modes and W=O stretching modes. It is noteworthy that the formation of crystalline WO₃ phase as observed in XRD and TEM measurements.⁴⁸

The FT-IR spectra of meso-SnO₂ and the WO_x/meso-SnO₂ materials with different WO_x contents are presented in Fig. S2.†

As reported in the literature,⁴⁹ the peaks at 651 cm⁻¹ and 553 cm⁻¹ could be assigned to different vibration modes of O–Sn–O and Sn–O–Sn groups. For WO_x/meso-SnO₂ materials,

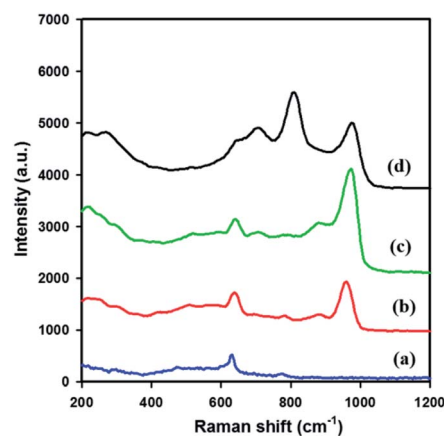


Fig. 3 Raman spectra of (a) meso-SnO₂, (b) 10 wt% WO_x/meso-SnO₂, (c) 20 wt% WO_x/meso-SnO₂, and (d) 30 wt% WO_x/meso-SnO₂.



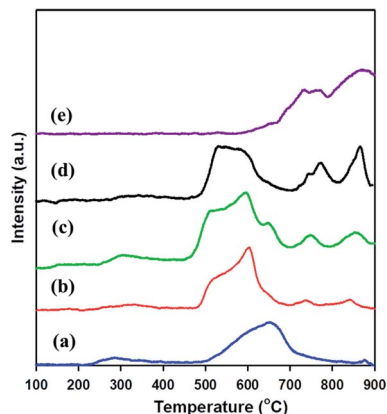


Fig. 4 H₂-TPR Profiles of (a) meso-SnO₂, (b) 10 wt% WO_x/meso-SnO₂, (c) 20 wt% WO_x/meso-SnO₂, and (d) 30 wt% WO_x/meso-SnO₂.

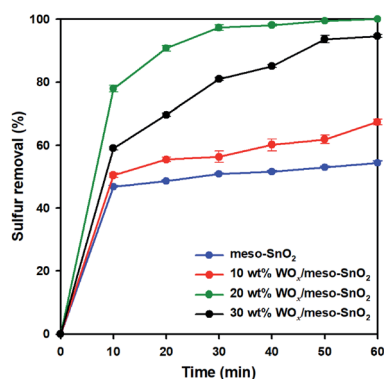


Fig. 5 Effect of different catalyst on removal of DBT from mode oil. Reaction conditions: mode oil = 14 mL, acetonitrile = 14 mL, sulfur concentration = 2000 ppm, catalyst = 0.1 g, $n[\text{H}_2\text{O}_2] : n[\text{S}] = 5 : 1$, reaction temperature = 50 °C, time = 60 min.

a peak appeared at 970 cm^{-1} was assigned to the stretching modes of W–O bond or W=O bond. Another new peak at 868 cm^{-1} demonstrated the typical Sn–O–W modes,⁵⁰ indicating the presence of strong interactions between highly dispersed WO_x and meso-SnO₂. Additionally, the peak at 1621 cm^{-1} was attributed to the bending vibrations of

hydrogen-bonded surface OH groups of physically adsorbed water molecules.⁵¹

H₂-TPR was examined to investigate the reducibility of meso-SnO₂ and WO_x/meso-SnO₂ catalysts. As shown in Fig. 4, the TPR profile of bulk WO₃ exhibited two high intensity peaks of hydrogen consumed beginning at 600 °C, centered at 770 and 870 °C. It is important to note that these peaks might be assigned to the stepwise reduction of WO₃ to W [WO₃ → W₂₀O₅₈ → WO₂ → W].⁵² The TPR profile of pure meso-SnO₂ exhibited a mainly reduction peak at about 652 °C, which could be assigned to the reduction of Sn(4+) → Sn(2+) → Sn(0). After impregnated WO_x, the first reduction peaks of all the WO_x/meso-SnO₂ catalysts shifted to lower temperature, indicating the presence of interaction between WO_x species and meso-SnO₂ support. Simultaneously, the relative area of this reduction peak increased with increasing WO_x concentration due to the increasing fraction of WO_x species in domains. The reduction temperature of the first peak at 450–550 °C was probably attributed to the reduction of octahedrally coordinated WO_x species as reported by Wachs *et al.*⁵³ Octahedrally coordinated WO_x species were found to be reduced at temperatures varying from 300 to 600 °C through intermediate oxidation states. Accordingly, the reduction peaks at 450–700 °C were assigned to the WO₃ to WO_{2.9} (or WO₂) reduction process and the reduction of SnO₂. The other two peaks located at higher temperature between 740 °C and 900 °C were probably attributed to a further reduction process of partially reduced WO_x species (WO_{2.9} → WO₂ → W) formed in the first reduction peak, together with the reduction of tetrahedrally coordinated WO_x species that interacted with SnO₂ support.^{54,55} In the case of 30 wt% WO_x/meso-SnO₂ catalyst, there were three reduction peaks centered at 743, 770, 867 °C, similar to those of bulk WO₃, indicating the formation of crystalline WO₃ on the surface of meso-SnO₂ support. In the case of 30 wt% WO_x/meso-SnO₂ catalyst, there were three reduction peaks centered at 743, 770 and 867 °C, similar to those of bulk WO₃, indicating the formation of crystalline WO₃ on the surface of meso-SnO₂ support.

3.2 Catalytic study

Fig. 5 shows the catalytic performance of pure meso-SnO₂ and WO_x/meso-SnO₂ catalysts for the removal of DBT from model oil, which were carried out at 50 °C with H₂O₂ as oxidant for 2 h.

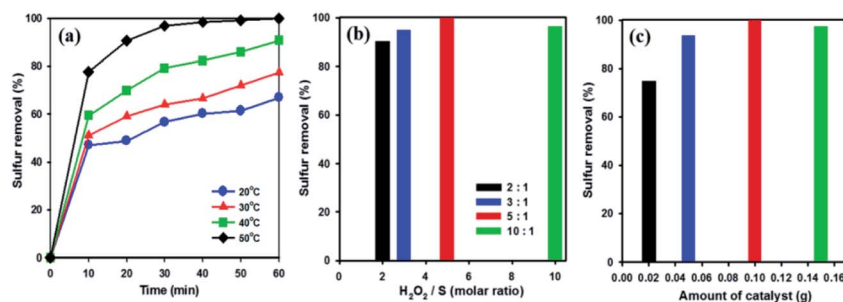


Fig. 6 Effect of (a) reaction temperatures, (b) molar ratio of H₂O₂/S, and (c) amount of catalyst on removal of DBT from model oil over 20 wt% WO_x/meso-SnO₂ catalyst reaction conditions: model oil = 14 mL, sulphur concentration = 2000 ppm, catalyst = 0.1 g, $n[\text{H}_2\text{O}_2] : n[\text{S}] = 5 : 1$, time = 60 min.



WO_x supported catalysts (WO_x/meso-SnO₂) exhibited better catalytic performance than pure SnO₂ support because the surface tungsten-oxo species (W=O) as the active sites could interact with H₂O₂ to form surface peroxo-tungsten (W-O-O-H) species, and then DBT was oxidized to DBTO₂ *via* oxidation process.⁵⁶ Therefore, the amount of WO_x loaded on meso-SnO₂ immensely influenced the desulfurization efficiency. As shown in Fig. 5, the desulfurization efficiency of WO_x-supported catalysts was remarkably increased with increasing WO_x concentration and reached the 100% removal with 20 wt% WO_x loading. The reason is because the active sites of tungsten-oxo species of 20 wt% WO_x/meso-SnO₂ catalyst are more than those of other catalysts. Further increase the WO_x loading up to 30 wt% resulted in the decrease catalytic removal of DBT (94.5%). This phenomenon may be ascribed to the excess of 20 wt% WO_x caused aggregation of tungsten oxide on the surface of meso-SnO₂ and the formation of crystalline WO₃ lead to a smaller surface area as shown in BET results (Table 1).

In order to examine the influence of reaction temperatures on the removal of DBT, a series of experiments were performed at different temperatures using 20 wt% WO_x/meso-SnO₂ catalyst. As shown in Fig. 6(a), raising the reaction temperature from 20 °C to 50 °C resulted in a remarkable increase in DBT removal efficiency and complete removal at 50 °C after 60 min. This indicates that the higher temperature is beneficial for H₂O₂ oxidation because the higher oxidation reaction rate at low temperatures might be limited by kinetics.⁵⁷ According to the above analysis, 50 °C was chosen as the optimal reaction temperature in this work.

H₂O₂ is one of the main factors in oxidative system. Hence, oxidative desulfurization of DBT was carried out under different molar ratios (from 2 to 10) of H₂O₂/S at 50 °C with 20 wt% WO_x/meso-SnO₂ as catalyst. As shown in Fig. 6(b), the DBT removal efficiency was increased with increasing the molar ratio of H₂O₂/S from 2 to 5 followed by a slight decreased at molar ratio of 10. This indicates that the excess oxidant is beneficial for increasing the reaction efficiency in heterogeneous catalysis.⁵⁸ According to the stoichiometry of the ODS reaction, 2 mole of H₂O₂ are consumed for the conversion of 1 mole of sulfur-containing compounds to their corresponding sulfones (DBTO₂).⁵⁹ However, the molar ratio of 2 gives only 90.3% of the sulfur removal, whereas the DBT can be removed completely from the model oil at the H₂O₂/S molar ratio of 5. The optimum ratio of H₂O₂/S was found to be 5, indicating that the H₂O₂ not only reacting with DBT, but also taken its self-decomposition. Therefore, stoichiometric amount of H₂O₂ can not result in complete oxidation of DBT under the present reaction conditions.

The amount of catalyst also affects desulfurization efficiency on the removal of DBT. As shown in Fig. 6(c), the sulfur removal increased from 74.7% to 100% in 60 min, when the amount of catalyst increased from 0.02 to 0.1 g. Below 0.1 g catalyst amount, the active sites of the catalyst were not enough to catalysis oxidative oxidize DBT completely. Nevertheless, when the catalyst amount increased to 0.15 g, the removal efficiency for DBT decreased to 97.2%. Therefore, the excessive catalyst was unnecessary in the desulfurization reaction because the excess active sites of catalyst might be covered by the absorption and

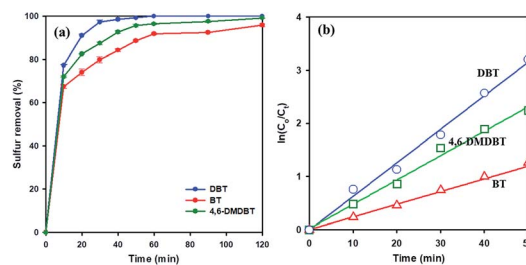


Fig. 7 (a) Oxidative desulfurization of different sulfur-containing compounds over 20 wt% WO_x/meso-SnO₂ catalyst. (b) Pseudo-first-order kinetics for DBT, BT, 4,6-DMDBT. Reaction conditions: model oil = 14 mL, acetonitrile = 14 mL, sulfur concentration = 2000 ppm, catalyst = 0.1 g, $n[\text{H}_2\text{O}_2] : n[\text{S}] = 5 : 1$, time = 120 min.

aggregation among the catalyst in a certain reaction volume, resulting the limitation of active sites actually contacted with sulfur-containing compound.⁶⁰ Thus, 0.1 g catalyst was chosen as the optimal amount for ODS reaction.

To study the effect of different sulfur-containing compounds in ODS reaction over 20 wt% WO_x/meso-SnO₂ catalyst. Beside DBT, benzothiophene (BT), and 4,6-dimethyl-dibenzothiophene (4,6-DMDBT), are also inflexible to be removed from fuels. The results in Fig. 7(a) indicated that the catalytic activity of these sulfur-containing compounds decreased in the order of DBT (100%) > 4,6-DMDBT (99.2%) > BT (94.4%) under the same experimental conditions. It may be ascribed to the different electron density of sulfur atoms on BT (5.739), DBT (5.758), and 4,6-DMDBT (5.760). In general, lower electron density on sulfur atom resulted in lower activity of the sulfur removal rate. Therefore, the lower electron density of sulfur atom on BT directly resulted in lowest sulfur removal efficiency.^{61,62} Moreover, compared to DBT, 4,6-DMDBT with two methyl groups on the benzene caused steric hindrance effect, leading to the active species hard to approach the sulfur atom. Therefore, the desulfurization efficiency of 4,6-DMDBT was lower than that of DBT.

To understand ODS kinetics, the kinetics parameters of DBT oxidation at different temperatures (20 °C, 30 °C, 40 °C, and 50 °C) were studied. The rate constants for the apparent consumption of DBT were obtained from the pseudo-first-order equation:

$$\ln(C_0/C_t) = kt \quad (1)$$

wherein, C_0 and C_t were the sulfur concentrations at time zero and time t (min), respectively, k was the rate constant (min^{-1}). As shown in Fig. S3(A),† a plot of $\ln(C_0/C_t)$ versus reaction time (t) displayed a linear relationship that confirmed the pseudo-first order reaction kinetics. The apparent rate constants of DBT were 0.0008, 0.016, 0.036 and 0.063 min^{-1} at 20 °C, 30 °C, 40 °C, and 50 °C, respectively. Based on the reaction rates at different temperatures, the apparent activation energy of DBT oxidation was derived from the Arrhenius equation:

$$E_a = RT^2(d\ln k/dT) \quad (2)$$

$$t_{1/2} = 0.693/k \quad (3)$$



Table 2 Rate constant k , half-live $t_{1/2}$, and correlation coefficient R of BT, DBT, and 4,6-DMDBT

Sulfur compound	Rate constant k (min^{-1})	Half-live $t_{1/2}$ (min)	Correlation coefficient R
DBT	0.0631	10	0.9929
4,6-DMDBT	0.0458	15	0.9903
BT	0.0260	26	0.9951

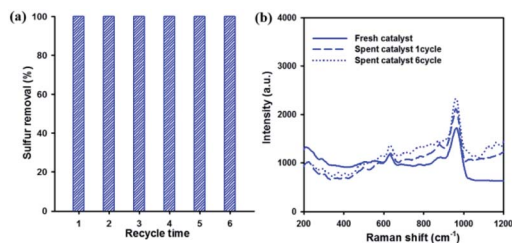


Fig. 8 (a) Recycle tests of 20 wt% $\text{WO}_x/\text{meso-SnO}_2$ catalyst. Reaction conditions: model oil = 14 mL, acetonitrile = 14 mL, sulfur concentration = 2000 ppm, $n[\text{H}_2\text{O}_2] : n[\text{S}] = 5 : 1$, catalyst = 0.1 g, reaction temperature = 50 °C, time = 60 min. (b) Raman spectra of fresh and spent catalysts.

where, E_a is the apparent activation energy, R and T are the gas constant and reaction temperature, respectively. Through the Arrhenius plot as shown in Fig. S3(B),† the activation energy of DBT is 54.8 kJ mol^{-1} . Zhu *et al.*¹⁸ have reported that the activation energy of DBT is 76.2 kJ mol^{-1} in the polyoxometalates/ H_2O_2 catalytic system. In $\text{AcOH}/\text{H}_2\text{SO}_4/\text{H}_2\text{O}_2$ system the activation energy of DBT oxidation is 57 kJ mol^{-1} , reported by Ukkirapandian *et al.*⁶³ The oxidation kinetics of BT and 4,6-DMDBT were also investigated under the optimal conditions. The plot of $\ln(C_0/C_t)$ versus time is shown in Fig. 7(b). Half-life was calculated by eqn (3). The rate constants k of DBT, BT, and 4,6-DMDBT were 0.0631 min^{-1} , 0.0260 min^{-1} , and 0.0458 min^{-1} , respectively. The half-life $t_{1/2}$ and correlation coefficients R are summarized in Table 2.

Reusability and stability of the catalyst are very important factors in industrial applications. Therefore, the reusability of the catalyst for DBT removal was investigated over 20 wt% $\text{WO}_x/\text{meso-SnO}_2$ catalyst. After each run, the used catalyst without any treatment (*i.e.*, solvent washing, recalcination) was separated from the reaction mixture by centrifugation. Then, fresh H_2O_2 and model oil were directly added into the original reaction round-bottom flask for the next run. Fig. 8(a) showed that the sulfur removal efficiency remained at 100% after recycling for 6 times. That is because the active tungsten species are present on the surface of meso-SnO_2 after recycling ODS reactions, as shown in the Fig. 8(b) Raman spectra. The results indicated that the 20 wt% $\text{WO}_x/\text{meso-SnO}_2$ has an excellent recycling performance in the deep oxidation desulfurization.

4. Conclusions

Highly ordered mesoporous $\text{WO}_x/\text{meso-SnO}_2$ catalysts with high surface area and well-defined mesoporosity were

successfully prepared by the nano-replication method and applied to oxidative desulfurization reaction for the first time. In this ODS system, through the optimization of reaction conditions, sulfur removal of DBT could reach 100% under 50 °C with 20 wt% $\text{WO}_x/\text{meso-SnO}_2$ as catalyst. Furthermore, 20 wt% $\text{WO}_x/\text{meso-SnO}_2$ catalysts also exhibited excellent recycling performance after recycling six times without losing catalytic activity, when the catalyst was used without any regeneration process during the recycle tests. This high catalytic activity and reusability may be ascribed to the well dispersed WO_x species and a strong interaction (synergistic effect) between WO_x and meso-SnO_2 . This system with a simple $\text{WO}_x/\text{meso-SnO}_2$ catalyst has a remarkable advantage over the desulfurization by more solvent extraction and provides a promising approach for the sulfur removal in the chemical industry.

Conflicts of interest

There are no conflicts to declare.

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