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# Introduction

Thermochemical sulfur cycles coupled with nuclear heat sources are considered to be practical water-splitting processes for substantial hydrogen production.<sup>1–4</sup> All the cycles investigated involve the requisite sulfuric acid (SA) decomposition reaction for the cyclic process. The sulfuric acid decomposition reaction occurs in two steps, *i.e.* the non-catalytic thermal decomposition of acid into SO<sub>3</sub> and H<sub>2</sub>O at temperatures above  $\sim 350$  °C, and the subsequent catalytic decomposition of SO<sub>3</sub> at temperatures above  $\sim 650$  °C to SO<sub>2</sub> and O<sub>2</sub>. The two-step

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# Pt-core silica shell nanostructure: a robust catalyst for the highly corrosive sulfuric acid decomposition reaction in sulfur iodine cycle to produce hydrogen<sup>†</sup>

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The platinum core silica shell catalyst has facilitated stable sulfuric acid decomposition at hightemperature which was not possible over bare Pt nanoparticles due to sintering and agglomeration. Helium (He) gas supplies the heat (550–900 °C) in a high temperature gas cooled reactor (VHTR). The major challenge is designing a stable catalyst for the variable heat efficiency of He. Pt catalysts loaded on different supports, such as SiC, Al<sub>2</sub>O<sub>3</sub>, SiC-Al<sub>2</sub>O<sub>3</sub>, BaSO<sub>4</sub>, TiO<sub>2</sub>, SBA-15, and SiO<sub>2</sub>, have been extensively studied but they have not provided a simple method to form robust catalysts for sulfuric acid decomposition. The core–shell scheme, whereby nanoparticles are enclosed by protecting agents (CTAB) and are covered by a silica shell, delivered mesopores and exhibited higher activity and stability over testing for more than 100 h. TEM images confirmed that the Pt particles on the Pt@mSiO<sub>2</sub> catalyst are more stable during sulfuric acid decomposition, and no significant evidence of agglomeration or sintering of the Pt core particles was found, despite some broken shells and dislocated Pt nanoparticles from the silica core. ICP-OES analysis of the spent catalysts after 100 h showed minimal Pt loss (9.0%). These types of catalysts are highly desirable for practical applications.

dissociation process is as follows, sulfuric acid thermal dissociation:

$$H_2SO_4$$
 (l)  $\Leftrightarrow$   $SO_3$  (g) +  $H_2O(g)$ ;

sulfur trioxide catalytic decomposition:

$$SO_3(g) \Leftrightarrow SO_2(g) + 1/2O_2(g)$$

The nuclear hydrogen generation cycle absorbs heat from pressurized He gas at high temperatures (550-900 °C). Therefore, the selection of catalyst candidates requires special attention, as the catalyst needs to be active and stable over this broad temperature window in a corrosive reaction environment. The catalytic breakdown of SO3 was significantly improved when SiO<sub>2</sub>,<sup>5,6</sup> SiC,<sup>7-11</sup> TiO<sub>2</sub>,<sup>12,13</sup> Al<sub>2</sub>O<sub>3</sub>,<sup>14-16</sup> ZrO<sub>2</sub>,<sup>12</sup> and BaSO<sub>4</sub><sup>17</sup> were employed as support materials for Pt, copper oxide (CuO), and Fe<sub>2</sub>O<sub>3</sub> catalysts.<sup>18</sup> CuO supported on SiO<sub>2</sub> emerged as a stable catalyst compared to Pt/Al2O3. However, deactivation was recorded at lower temperatures (less than 600 °C).5 Lee et al. studied sulfuric acid decomposition at 650 °C-850 °C using Pt/Al2O3 and Pt-SiC- $Al_2O_3$  catalysts.<sup>14</sup> Similar to the results obtained by Machida *et al.*,<sup>5</sup>  $Pt/Al_2O_3$  showed no or much less decomposition of SO<sub>3</sub>, which was entirely deactivated in a short time. Pt-loaded SiC-Al2O3 was stable for a longer time and deactivation due to sulfation (poisoning) of Pt/Al<sub>2</sub>O<sub>3</sub> was significantly controlled because of the resistance of



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SiC to sulfation.<sup>8</sup> Previous literature has reported that Al<sub>2</sub>O<sub>3</sub> can typically form aluminum sulfate at temperatures <700 °C,<sup>16</sup> however, for the Pt/SiC-Al<sub>2</sub>O<sub>3</sub> catalyst, no evidence of poisoning (sulfation) was reported. Mixed metal oxide catalysts (CuCr<sub>2</sub>O<sub>4</sub>, Fe-Cr oxide, CuO-V<sub>2</sub>O<sub>5</sub>, and CuO<sub>2</sub>/CeO<sub>2</sub>) performed better at high temperatures, but their ability to perform at low temperatures limited their application as alternatives to Pt-based catalysts.<sup>5,19-21</sup> Porous Cu-V (oxide)/SiO<sub>2</sub> showed promising catalytic activity for SO<sub>3</sub> decomposition at temperatures from 800 to 650 °C, but its stability remained a challenge.<sup>5,19,22</sup> In recent reports, a CuO-CeO<sub>2</sub> complex oxide catalyst has been reported as a comparable candidate to Pt for SO<sub>3</sub> decomposition,<sup>23</sup> however the higher activity and extended stability are not satisfactory at temperatures >700 °C, due to sulfate formation.

Therefore, alternatives to Pt-based catalysts for different ranges of temperature have been investigated, but low temperature stability remains a challenge. Pt is considered to be highly active and stable, but factors associated with the deactivation of Pt-based catalysts include sintering and leaching of Pt due to its volatile behavior at high temperatures in an oxidizing environment. Other factors include support associated deactivation and low metal support interactions.

It has been known for many years that interactions between metal catalysts and oxide supports are significant for changing the properties of a catalyst, and that core–shell nanostructure catalysts are promising in enhancing these metal–metal oxide interactions. The Pt/SiO<sub>2</sub> catalyst was stable at wide temperature ranges, but long time stability tests showed deactivation due to Pt loss at high temperatures.<sup>6</sup> The unique metal core and metal oxide shell structures are regarded to be an effective way of preventing metal nanoparticle agglomeration or deformation.<sup>24</sup> Several core–shell nanoparticles, consisting of a metal core and a metal–oxide shell, have been synthesized such as SiO<sub>2</sub>, ZrO<sub>2</sub>, TiO<sub>2</sub>, and carbon. However, mesoporous silica has attracted great attention because of its attractive properties, *i.e.* control over its physiochemical properties (surface area, pore volume, and diameter) and its extraordinary thermal stability.

Here, we report a one-pot method to prepare a stable model catalyst for a high temperature sulfuric acid decomposition reaction. The catalyst is based on a Pt metal core coated with a mesoporous silica shell (Pt@mSiO<sub>2</sub>). The Pt nanoparticles in the core remain unchanged up to 900 °C and the Pt@mSiO<sub>2</sub> nanoparticles provide the catalytically active bare Pt metal for the sulfuric acid decomposition reaction, as the inorganic mesoporous silica shells provide direct access to the Pt core. Pt@mSiO<sub>2</sub> addresses the stability and platinum loss issues, which have been observed for Pt nanoparticles supported on the surface of support materials, due to their aggregation and leaching during the reaction. The results indicate that the Pt@mSiO<sub>2</sub> nanoparticles are excellent nanocatalysts, and are practical solutions for corrosive, high temperature applications.

# **Experimental details**

#### Catalyst synthesis

A Pt core-shell  $SiO_2$  shell was prepared as follows: 0.10 g of cetrimonium bromide (CTAB) surfactant was dissolved in a

solution containing 48 mL of deionized water and 1.2 mL of 0.5 M NaOH. After stirring at 80 °C for 15 min, 2 mL of 3.7% formaldehyde solution was added. The calculated amounts of Pt (1.0 wt%) using a  $k_2$ PtCl<sub>4</sub> (Sigma Aldrich) precursor mixed in 4 mL water were added to the above solution. A separate solution containing 0.53 mL of tetraethyl orthosilicate (TEOS) and 1.3 mL of ethanol was added after stirring for an additional 10 min. The reaction was allowed to continue for 1 h and the precipitated products were separated by centrifugation at 8000 rpm and then washed with deionized (DI) water and ethanol. The recovered products were dried overnight at 80 °C. Removal of the CTAB template was achieved by calcination at 550 °C for 6 h. The temperature was increased at a rate of 1 °C min<sup>-1</sup>. The prepared Pt@mSiO<sub>2</sub> particles were heat treated at 850 °C in N<sub>2</sub>, before being subjected to the SA decomposition reaction.

#### Characterization

The X-ray diffraction (XRD) analysis of the pristine and spent samples was recorded on a diffractometer (M/S Shimadzu Instruments, Japan) using Cu K $\alpha$  ( $\lambda$  = 0.154 nm) radiation. The operating voltage was 40 kV, and the current was 30 mA. Surface areas, pore volumes, and pore sizes were obtained from Ar physisorption analysis. Argon adsorption measurements were carried out at 87 and 77 K using a Micrometrics ASAP-2010 static volumetric adsorption analyzer. This was equipped with 1000, 10, and 1 torr pressure transducers and was used to accurately measure argon adsorption data in the relative pressure range of 10.6-10.7 to 0.99. High purity (99.999%) argon was used for the measurements. Prior to the measurements, all samples were degassed under argon at 473 K for 4 h. The morphologies of the prepared catalysts were detected using transmission emission microscopy (TEM-Technai microscope; FEI G2). ICP-OES (inductively coupled plasma-optical emission spectroscopy) analysis was used to determine the Pt metal content in the pristine and spent catalysts (ICP-OES iCAP-6000 series, Thermo USA).

#### Activity measurements

The catalytic activity was tested in a bayonet-type quartz reactor at 650, 750, and 850 °C. Catalyst stability was tested at a gas hourly space velocity (GHSV) of 76 000 mL  $g_{cat}^{-1}$  h<sup>-1</sup>. The length of the reactor was 55 cm, and the inner and outer diameters were 8.0 and 28 mm, respectively. The feed molar ratio of sulfuric acid to N<sub>2</sub> was 1:1. The flow rates of 85% sulfuric acid and nitrogen gas were 0.25 g min<sup>-1</sup> (liquid phase, 25 °C) and 95 mL min<sup>-1</sup> (gas phase). The GHSV in the typical reaction conditions was 76 000 mL  $g_{cat}^{-1}$  h<sup>-1</sup>. Sulfuric acid (SA, purity: 85 wt%) was injected into the reactor through an evaporator by a liquid micro-pump. The O<sub>2</sub> from the H<sub>2</sub>SO<sub>4</sub> trap was analyzed by gas chromatography (Young Lin Inc. – M600D).

### **Results and discussion**

#### Effective one-pot synthesis method

The synthesis scheme of the Pt core and mesoporous silica shell ( $Pt@mSiO_2$ ) by a one-pot method is speculated to occur as follows (Scheme 1).



Scheme 1 A schematic illustration of the core shell Pt@mSiO<sub>2</sub> one-pot synthesis method: (a) a solution of H<sub>2</sub>O, NaOH and CTAB; (b) CTAB-stabilized Pt particles; (c) Pt covered by surrounding silica micelles; (d) Pt nanoparticles coated by a thin layer of silica; (e) Pt cores encapsulated in a silica shell.

CTAB surfactant was mixed in water under basic conditions using NaOH at 80 °C. K<sub>2</sub>PtCl<sub>4</sub> was added to solution (a), and formaldehyde was used as a reducing agent. CTAB-stabilized Pt nanoparticles started to form after 10 minutes, and the solution was stirred for 15 minutes before adding TEOS and ethanol to solution (b). The TEOS started to condense after 20 minutes and the color of the solution started to change at steps c and d. The reaction continued for 1 hour, and the color started to change whilst the silica spheres started to grow in size. The mechanism proposed by Chen et al.25 suggested that two main changes occur during the formation of Pt@mSiO<sub>2</sub>, and these include the growth of mesoporous silica shells and the reforming process of the particles according to the principle of lowest energy to form nano-spheres with Pt in the cores. The reaction time was extended further (>1 h) during step (d), but no significant changes in morphology were noticed. This clarified that the growth of the silica spheres stopped and that Pt was settled well within the cores. After removing the CTAB in the calcination step, silica-coated Pt nanoparticles were recovered.

#### Catalytic performance of the Pt@mSiO<sub>2</sub> catalyst

The catalytic performance of the prepared  $Pt(\underline{3})mSiO_2$  catalyst was investigated. The effects of sulfuric acid contact time on decomposition are shown in Fig. 1(a). It is evident that at a low contact time, low activity is recorded, and at a high contact time, high activity is recorded. The conversion reached equilibrium with increasing contact time at a space velocity of 46 000 mL  $g_{cat}^{-1}$  h<sup>-1</sup>. The stability of



Pt@mSiO<sub>2</sub> was recorded at a higher GHSV of 76 000 mL  $g_{cat}^{-1}$  h<sup>-1</sup>, in order to observe the deactivation behavior away from the equilibrium conversion. The recorded results are presented in Fig. 1(b). No indication of noticeable deactivation was found during 100 h of reaction at 850 °C (Fig. 1(b)). The recorded initial conversion was  $\sim$  77% at a high temperature (850 °C) and was 27% at a low temperature (650 °C). It was observed that the final conversion after 100 h exposure to sulfuric acid was 75% and 24%, respectively. In order to determine the superior performance of the Pt@mSiO<sub>2</sub> catalyst, sulfuric acid decomposition was performed on Pt/TiO2 and Pt/Al<sub>2</sub>O<sub>3</sub> catalysts, and the data is presented in Fig. S1 (ESI<sup>+</sup>). The Pt/Al<sub>2</sub>O<sub>3</sub> catalyst shows no activity at 650 °C due to alumina sulfate formation, and this is extensively recorded in the literature.14,26 XRD patterns clearly showed the Al2SO4 peaks that are mentioned in Fig. S2 (ESI<sup>†</sup>). Pt/TiO<sub>2</sub> and Pt/Al<sub>2</sub>O<sub>3</sub> also showed deactivation in a high-temperature reaction at 850 °C after 40 h, and this was later confirmed by different characterization techniques. It was found that Pt loss at high temperatures and a high GHSV was the reason for deactivation. Previous reports of sulfuric acid decomposition over Pt/Al2O3 showed that the catalyst is stable at a low GHSV, where the catalyst is exposed to a low SA flux, however, because the high GHSV catalyst shows strange behavior, Pt loss becomes the reason for deactivation. The initial activity of the Pt/TiO<sub>2</sub> (Rutile) catalyst was nearly equal to that of Pt@mSiO<sub>2</sub>, but the catalyst showed a 20% fall in activity over time. The reason for deactivation was ascribed to platinum loss when ICP-OES analysis was performed.

#### **Physisorption studies**

Fig. 2(I) shows the BJH pore size distribution of the (a) pristine catalyst, (b) spent catalyst at 650 °C for 100 h, and (c) spent catalyst at 850 °C for 100 h. The surface area and pore size values are given in Table 1. The surface area of the pristine catalyst was 679 m<sup>2</sup> g<sup>-1</sup> and the pore size was 3.86 nm. It can be seen from Fig. 2(II) that the Pt@mSiO<sub>2</sub> materials show type-IV isotherms. Significant decreases in the surface areas after sulfuric acid decomposition for 100 h are recorded. The surface area of the high temperature (650 °C) spent catalyst is 60.9 m<sup>2</sup> g<sup>-1</sup> and that of the high temperature (850 °C) spent catalyst is 60.9 m<sup>2</sup> g<sup>-1</sup>. The surface areas of Pt/Al<sub>2</sub>O<sub>3</sub> and Pt/TiO<sub>2</sub> were also measured and are given in Table 1. Bimodal pores with two ranges of pore size distributions are found in the Pt@mSiO<sub>2</sub> catalyst (see Fig. 2(I) and b).



**Fig. 2** BET pore size distributions and N<sub>2</sub>-isotherms of the Pt@mSiO<sub>2</sub> catalysts: (I) BJH pore-size distributions, and (II) adsorption–desorption isotherms of (a) the Pt@mSiO<sub>2</sub> pristine catalyst, (b) the spent catalyst at 650 °C, and (c) the spent catalyst at 850 °C for 100 h at GHSV of 76 000 mL  $g_{cat}^{-1}$  h<sup>-1</sup>.

Table 1 BET surface area and pore size information of the pristine and spent catalysts

Catalyst	$S_{\rm A} \left( {{\rm{m}}^2 \; {{\rm{g}}^{ - 1}}}  ight)$	$V_{\rm p}  ({\rm cm}^3  {\rm g}^{-1})$	$D_{\rm p}~({\rm nm})$	Average Pt crystal size <sup>a</sup> (nm)	ICP-OES wt (%)
Pt@mSiO <sub>2</sub> pristine	676.9	0.69	3.86	3.9	0.89
Pt/TiO <sub>2</sub> pristine	49.5	0.44	35.94	_	0.82
$Pt/Al_2O_3$ pristine	29.3	0.18	24.13	_	0.78
Pt@mSiO <sub>2</sub> —650/100 h reaction	466.0	0.49	4.52	4.02	0.85
Pt-Al <sub>2</sub> O <sub>3</sub> -650/100 h reaction	2.09	0.26	504.83	_	_
Pt-TiO <sub>2</sub> 650/100 h reaction	2.50	0.022	28.62	_	0.53
$Pt-Al_2O_3$ 850/100 h reaction	10.9	0.2036	78.81	_	0.49
Pt@mSiO <sub>2</sub> -850/100 h reaction	60.9	0.4324	28.32	11.02	0.81
Pt-TiO <sub>2</sub> -850/100 h reaction	6.9	0.03	19.71	_	0.54
<sup><i>a</i></sup> Crystal size calculated using the	Scherrer equation.				

The development of such large pores is mainly considered to be a realistic approach to decrease the mass transfer resistance of reactants and products in the presence of multiple intermediate gas species in the reaction condition. However, the change in surface area after the reaction may result from structural changes at high temperatures. Sintering and fracturing of the  $SiO_2$  shell results in a decreased surface area.

#### XRD analysis of the pristine and spent catalysts

Fig. 3 shows the XRD analysis of the pristine and spent catalysts. The XRD patterns of the Pt@mSiO<sub>2</sub> sample correspond to cubic Pt. The Pt@mSiO<sub>2</sub> catalyst showed low intensity diffraction peaks of metallic Pt with a Pt loading amount of 1 wt% at  $2\theta$  degrees of 39.7(111), 46.2(200) and 67.5(200), indicating a uniform dispersion [PDF 04-0802]. The crystal size of Pt, calculated using the Scherrer equation, is 3.0 nm for the pristine catalyst. The spent catalysts showed crystal sizes of 4.05 nm at 650 °C and 11.02 nm at 850 °C after a 100 h reaction. It can be seen that the high temperature (850 °C) spent catalyst shows an increase in crystal size. During the TEM analysis, some broken SiO<sub>2</sub> spheres were recorded with empty cores, but these kinds of images have not been detected in the pristine



Fig. 3 X-ray diffraction analyses of (a) pristine Pt@mSiO<sub>2</sub>, (b) spent catalyst at 650 °C, and (c) the spent catalyst at 850 °C for 100 h at a space velocity of 76 000 mL  $g_{cat}^{-1}$  h<sup>-1</sup>.

catalysts. The likely reason for this is that the growth of the crystal size stems from the migrated Pt particles, which are initially inside the core of the SiO<sub>2</sub> sphere. No other phase or unwanted peaks of sulfate were noticed after 100 h of the sulfuric acid decomposition reaction at 650 or 850 °C. Compared to the Pt@mSiO<sub>2</sub> and Pt/TiO<sub>2</sub> catalysts, the Pt/Al<sub>2</sub>O<sub>3</sub> spent catalyst at 650 °C showed aluminum sulfate peaks, which are shown in Fig. S2 (ESI†). This clarified that that the catalyst with sulfate species at a low temperature deactivated quickly, while the catalyst that is resistant to poisoning and sulfating remains active and notably stable.

#### ICP-OES studies for quantitative analysis of the Pt component in the pristine and spent catalysts

In order to determine the promotional effect of the core-shell structures on the prevention of active Pt metal loss, data was collected from the literature for Pt catalysts deposited on the surface of catalysts. The reported values are compared in Table 2. It was reported that Pt impregnated on a SiC support was initially active. The loss of activity during the initial time (3 h) was probed and the loss of active Pt was a primary factor.<sup>7</sup> In another study, Pt supported on a hollow SiC (Pt/hSiC) support showed better stability for a 30 h reaction, but it showed that Pt was removed from the spherical shell region, due to the disintegration of the spherical morphology. Indeed, ultra-small Pt (1-2 nm) particles were preserved in the wall of the hollow region. No evidence of sintering was reported. The loss of Pt in the ICP-OES analysis was around 27%, which is quite high.<sup>10</sup> Pt supported on hollow SiO2(Pt-HMSS) showed better resistance to Pt loss, in long time reactions up to 50 h.<sup>6</sup> It could be seen that Pt in the hollow core region did not sinter and remained intact.

 Table 2
 Comparative analysis of metal loss in reported catalysts for the SA decomposition reaction

Catalyst	$r \times n$ (h)	Weight loss (%)	Ref.
Pt/SiC-AP	30	30	7
Pt/hSiC	50	27.5	10
Pt/SiO <sub>2</sub> @mSiO <sub>2</sub>	50	70.5	10
Pt/mesoporous SiC	50	25	11
Pt/SBA-15 impregnation	12	46.6	11
Pt-HMSS	50	17.5	6
Pt-TiO <sub>2</sub>	50	35.2	27
Pt/SBA-15 one-pot	100	14	28
Pt@mSiO <sub>2</sub>	100	9.0	Present work



Fig. 4 TEM images: (a1–a3) pristine Pt@mSiO<sub>2</sub> and (b1–b4) spent catalyst at 850 °C for 100 h at GHSV 76 000 mL  $g_{cat}^{-1}$  h<sup>-1</sup>.

However, due to the breakdown of the fragile shells, Pt detached and increased the sintering, but because most SiO<sub>2</sub> spheres remained after the reaction, less Pt loss (17%) was reported.<sup>6</sup> Pt/TiO<sub>2</sub> and Pt on SBA-15 showed Pt losses of nearly 35 to 40% and were severally deactivated. In the present study, Pt@mSiO<sub>2</sub> shows a Pt loss of ~9.0% after a 100 h reaction, and this is the lowest among all the reported catalysts for SA decompositions, which is in agreement with the superior catalytic performance. This also emphasizes the importance of core shells for producing catalysts that are fit for commercial applications.

# Morphology analysis of pristine and spent catalysts by TEM (transmission electron microscopy)

TEM images of Pt@mSiO<sub>2</sub> nanoparticles are shown in Fig. 4. It is evident that a single particle exists in the core with a silica shell. The average silica shell layer around the Pt core is  $\sim 62.5$  nm  $(\pm 5)$  and the size of the Pt nanoparticle core is  $5 (\pm 3)$  nm. Table 1 shows the crystal sizes, calculated from the Scherrer equation, and the particle size distributions from the TEM images given in Fig. 4. The average particle size from the TEM images is 6.0 nm for the pristine catalyst and 7.0 nm after 100 h reaction at 850 °C. Although there is a possibility that some particles might be sintered as the crystal size increases during XRD analysis, all the catalysts were calcined at 850 °C in N2 before the reaction and no evidence of sintering was found. Therefore, it can be noted here that high temperature is not the only factor for prompting sintering. Fig. 4(b2) shows some evidence that the core of the silica sphere is empty, and some broken spheres are also found. This clarifies that some of the Pt nanoparticles are sintered because of shell disintegration in the spent catalysts where the reaction environment is highly corrosive and strongly oxidative. It can therefore be suggested that the sintering temperature is approximately 0.8 times the melting temperature. The melting point of pure silicon is about 1450 °C, therefore the sintering temperature is about 1120 °C. Another factor that affects the temperature of fracturing is the rate at which the temperature is increased. If this is high enough, it can lead to the occurrence of a temperature gradient between the interior and exterior of the grain during heat treatment, resulting in heterogeneous thermal expansion and, thus, fracturing. The SA decomposition reaction is conducted at  $\sim$  850 °C, which is close to the sintering temperature. Some of the silica shells with low thickness tend to crack, however potential synergies originating from the interactions between the core and shell materials make the core-shell structure stronger.

# Conclusion

—Highly active catalysts are critical for developing the sulfuric acid decomposition process in the sulfur iodine cycle, in order to produce hydrogen.

—Pt core silica shell catalysts with porous shells were successfully fabricated through the sol-gel coating process.

—Remarkable results from the catalytic investigation of Pt@mSiO<sub>2</sub> for sulfuric acid decomposition indicate that the catalyst is relatively stable in the broad 550–850  $^{\circ}$ C temperature range.

—Several Pt-based catalytic systems have been studied, but they have not performed well over long periods of stability testing. Pt loss and Pt sintering by volatilization at high temperatures in oxidative reaction conditions seriously deactivated the catalyst. However, the core-shell catalyst restricted the Pt particles during the reaction, resulting in high stability.

—The Pt metal loss in the  $Pt@mSiO_2$  catalyst during SA decomposition was minimized.

—The Pt embedded structure resisted the loss of Pt and slowed down the sintering of Pt, demonstrating relatively high catalytic stability. Therefore, we can infer that these catalysts are significantly active for decomposing SO<sub>3</sub>.

### Conflicts of interest

There are no conflicts to declare.

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