



## Effects of particulates, heavy metals and acid gas on the removals of NO and PAHs by $V_2O_5-WO_3$ catalysts in waste incineration system

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### ABSTRACT

This study investigated the activities of prepared and commercial  $V_2O_5-WO_3$  catalysts for simultaneous removals of NO and polycyclic aromatic hydrocarbons (PAHs) and the influences of particulates, heavy metals,  $SO_2$ , and HCl on the performances of catalysts. The experiments were carried out in a laboratory-scale waste incineration system equipped with a catalyst reactor. The DREs of PAHs by prepared and commercial  $V_2O_5-WO_3$  catalysts were 64% and 72%, respectively. Increasing the particulate concentrations in flue gas suppressed the DRE of PAHs, but increasing the carbon content on surface of catalysts promotes the NO conversions. The DRE of PAHs by the catalysts was significantly decreased by the increased concentrations of heavy metal Cd, but was promoted by high concentration of Pb. The influence level of  $SO_2$  was higher than HCl on the performances of  $V_2O_5-WO_3$  catalysts for PAHs removal, but was lower than HCl for NO removal. Prepared and commercial  $V_2O_5-WO_3$  catalysts have similar trends on the effects of particulates, heavy metals,  $SO_2$ , and HCl. The results of ESCA analysis reveal that the presences of these pollutants on the surface of catalysts did not change the chemical state of V and W.

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### 1. Introduction

To conform to the strict environmental regulations and criteria in Taiwan, more and more catalysis technologies are applied to control the air pollutants emitted from the stationary sources, such as factories, power plants, and especially for the waste incinerators. The catalysis reactors will be incorporated into the air pollution control devices (APCDs) of existing waste incinerators in Taiwan. In most cases, the catalyst reactors are set up in the downstream of APCDs to mitigate the poisoning of catalysts. However, since the exhausts of waste incineration always contain complicated pollutants, including  $SO_2$ , HCl, heavy metals and particulates, they are difficult to be completely removed and will enter the catalyst reactor.

$V_2O_5-WO_3$  is the commonly used catalyst to simultaneously reduce the nitrogen oxides (NO) [1–3] and volatile organic compounds (PCDD/Fs, PCBzs, and PAHs) [4–7]. Additionally, the activity of  $V_2O_5-WO_3$  catalyst is more effective than the other catalysts at high oxygen concentration (6–10%) and low temperatures (200–300 °C) [8]. Some studies investigated the influences of  $SO_2$ , HCl, and alkali metals on the activity of  $V_2O_5-WO_3$  catalyst. Chen and Yang [9] indicated that  $SO_2$  can promote the activity

of  $V_2O_5-WO_3$  catalyst for NO reduction with  $NH_3$  as reductant, because  $SO_2$  gas can absorb on the active sites of catalysts to form sulfate and that can increase the Brønsted acidity of catalyst surface [9,10]. The poisoning effects of alkali metals on the catalysts may be attributed to their penetration into the catalysts to form complex compounds (V–O–K, for example) and decreasing the adsorption and reaction efficiencies [9]. Lisi et al. [11] also pointed out that the coexistence of K and HCl would completely poison the  $V_2O_5-WO_3$  catalysts as compared with single K. The alkali metal K poisoned the catalyst by decreasing its Brønsted acidity and HCl deactivated the catalyst by forming the volatile vanadium chlorides. The effect of particles on the catalysts was less investigated. Zheng et al. [12,13] indicated that particulates decreased the diffusion rate of NO into the catalysts by deposition and pore blocking.

Most studies regarding to  $V_2O_5-WO_3$  catalysts focused on the removal of NO and the influences of different pollutants, and they were performed in a small-scale tube reactor with simulated gases and reaction conditions. Few studies applied  $V_2O_5-WO_3$  catalyst to the removal of organic pollutants (PAHs) as well as performed in a real large-scale combustion system. Therefore, this study sets up a laboratory-scale waste incineration system which incorporated a catalysis reactor to investigate the performances of  $V_2O_5-WO_3$  catalysts for the simultaneous removal of PAHs and NO. The effects of different air pollutants (particulates, acid gases, and heavy metals) on the activities of catalysts were also investigated. Moreover, the poisoning mechanisms of different pollutants on the catalysts were

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**Table 1**  
Feedstock compositions and the target pollutant evaluated in each test.

Run	Feedstock composition (g per bag)						Target pollutant evaluated
	PE bag	Sawdust	Heavy metal	Sulfur	PVC	Water	
1	0.3	3.0				1.0	–
2	0.3	3.0				1.0	1.00 g/Nm <sup>3</sup> particulates
3	0.3	3.0				1.0	16.65 g/Nm <sup>3</sup> particulates
4	0.3	3.0	0.0165 Cd			1.0	0.5 wt% Cd
5	0.3	3.0	0.0660 Cd			1.0	2.0 wt% Cd
6	0.3	3.0	0.0165 Pb			1.0	0.5 wt% Pb
7	0.3	3.0	0.0660 Pb			1.0	2.0 wt% Pb
8	0.3	3.0		0.01		1.0	200 ppm SO <sub>2</sub>
9	0.3	3.0			0.035	1.0	200 ppm HCl
10	0.3	3.0		0.01	0.035	1.0	200 ppm SO <sub>2</sub> and 200 ppm HCl
11	0.3	3.0	0.0165 Cd + 0.0165 Pb	0.01	0.035	1.0	0.5 wt% Cd, 0.5 wt% Pb, 200 ppm SO <sub>2</sub> , and 200 ppm HCl

also evaluated through various characterization techniques, including scanning electron microscopy (SEM), elemental analyzer (EA), and electron spectroscope for chemical analysis (ESCA). The results will provide useful information for the designs and applications of catalysts in the waste incineration plants.

## 2. Experimental

### 2.1. Preparation of catalysts

Two V<sub>2</sub>O<sub>5</sub>–WO<sub>3</sub> catalysts were used in this study, one is prepared by ourselves and the other one is a commercial V<sub>2</sub>O<sub>5</sub>–WO<sub>3</sub> catalyst. The prepared V<sub>2</sub>O<sub>5</sub>–WO<sub>3</sub> catalyst was prepared by the co-impregnation method using ammonium metavanadate (NH<sub>4</sub>VO<sub>3</sub>) as precursor for V<sub>2</sub>O<sub>5</sub>, ammonium metatungstate hydrate (H<sub>26</sub>N<sub>6</sub>O<sub>40</sub>W<sub>12</sub>·xH<sub>2</sub>O) as precursor for WO<sub>3</sub>, and commercial Al<sub>2</sub>O<sub>3</sub> pellets (Alfa Aesar, 90 m<sup>2</sup>/g) as catalyst support. The contents of V and W in the catalysts were 0.3 and 0.9 wt%, respectively. After the co-impregnation procedure, the 0.3% V<sub>2</sub>O<sub>5</sub>–0.9% WO<sub>3</sub>/Al<sub>2</sub>O<sub>3</sub> catalysts were dried at 105 °C for 6 h and calcined at 500 °C for 6 h in air. The commercial V<sub>2</sub>O<sub>5</sub>–WO<sub>3</sub> catalyst was purchased from the Ymet Energy Company in Taiwan.

### 2.2. Preparation of feedstock for incineration

The artificial feedstock for the incineration experiments were composed of wood, heavy metals, sulfur powder, polyvinyl chloride (PVC) plastics and water to simulate the typical municipal solid waste in Taiwan [14,15]. To evaluate the effects of HCl, SO<sub>2</sub>, and heavy metals on the activities of prepared and commercial V<sub>2</sub>O<sub>5</sub>–WO<sub>3</sub> catalysts, the contents of PVC, sulfur, and heavy metals (Cd and Pb) in the feedstock were varied. Table 1 lists the compositions of artificial feedstock and the target pollutants evaluated in different tests. These materials were packed in a polyethylene (PE) bags and the total weight of each feedstock bag was 3.0–3.6 g. The nitrates of heavy metals Cd and Pb were dissolved in distilled water and added into the feedstock. Moreover, the influences of single and multiple pollutants (Pb, Cd, SO<sub>2</sub> and HCl) on the catalysts were investigated. The major chemical compositions (C, H, O, N) of feedstock in different experiments were carefully controlled to be similar even PVC was added for producing HCl. Therefore, the combustion parameters and the major compositions (CO<sub>2</sub>, O<sub>2</sub>, H<sub>2</sub>O, and N<sub>2</sub>) of exhausts were similar.

### 2.3. Apparatuses and procedures of catalyst tests

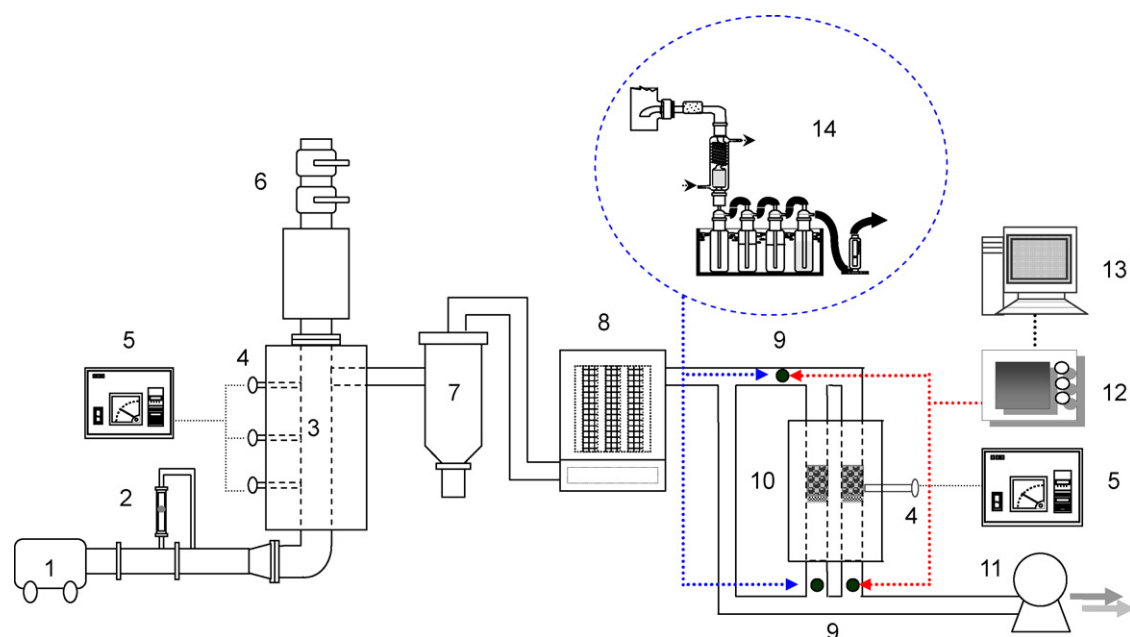
A laboratory-scale waste incineration system consisted of one combustion chamber, one cyclone, one bag filter, and one catalysis reactor was set up for the experiments (Fig. 1). Several thermo-

couples were inserted into each part of the incineration system to monitor and control the operating temperatures. The airflow rate supplied for the waste incineration was 75 L/min at room temperature. The combustion chamber and catalysis reactor were preheated by electric heaters and controlled at 850 and 250 °C, respectively. The artificial feedstock was continuously fed into the incinerator at regular intervals of 20 s per bag. The flue gas of waste incineration was passed through the cyclone and bag filter to remove particulates and then entered the catalysis reactor. To evaluate the effects of particulate matters on the catalysts, the different concentrations of particulates were controlled by changing the number of filters in the bag filter. The prepared and commercial V<sub>2</sub>O<sub>5</sub>–WO<sub>3</sub> catalysts were put into the catalysis reactor before conducting the experiments. The stability of waste combustion was checked by monitoring the variation of combustion temperatures and the concentrations of CO, CO<sub>2</sub>, and O<sub>2</sub>. After the concentrations of CO, CO<sub>2</sub> and O<sub>2</sub> reached a steady state, the exhaust was introduced into the catalysis reactor. The gas flow rate in the catalysis reactor was controlled at 6 L/min by a mass flow meter and a vacuum pump in the end. The corresponding space velocity of the catalysis reactor was 70,000 h<sup>-1</sup>. The concentrations of NO in the inlet and outlet gases of catalysis reactor were continuously measured by a stack gas analyzer. The sampling of PAHs was beginning at 10 min after the gas composition reached the steady state. The exhausts were finally treated by a wet scrubber and discharged into the atmosphere.

### 2.4. Sampling and analysis

The concentrations of O<sub>2</sub>, CO, CO<sub>2</sub>, NO and SO<sub>2</sub> in the inlet and outlet gases of catalysis reactor were continuously measured by a stack gas analyzer (HORIBA VIA-510). This analyzer was equipped with one chemiluminescence detector for NO measurement, one electrochemistry detector for O<sub>2</sub> measurement, and one non-dispersive infrared detector for measuring SO<sub>2</sub>, CO, and CO<sub>2</sub>. The destruction removal efficiency (DRE) of NO was defined as  $DRE = (C_1 - C_2)/C_1$ , where C<sub>1</sub> and C<sub>2</sub> is the concentration of NO in the inlet and outlet gases of catalysis reactor, respectively. The sampling and analysis of HCl were carried out by the standard method of Taiwan EPA (NIEA A453.70C). The sampling flow rate was controlled at 6 L/min and the sampling time was 10 min. Two impingers filled with 100 ml distilled water were used to absorb the HCl gas. After sampling, the impinger solutions were analyzed by an ion chromatograph (IC) (DIONEX DX-100).

The sampling and analysis methods for PAHs were modeled on US EPA modified method 5 (MM5). The flue gas was drawn out and passed through a heated glass-fiber filter to remove fine particles, and then passed through a cooling tube filled with XAD-16 adsorbents to capture gas-phase organic compounds. The sampling time was 10 min and the flow rate was



**Fig. 1.** Diagrammatic illustration of experimental apparatus: (1) air compressor, (2) flow meter, (3) combustion chamber, (4) thermocouples, (5) temperature controller, (6) feedstock feeder, (7) cyclone, (8) bag filter, (9) sampling points, (10) catalysis reactor, (11) induced fan, (12) stack gas analyzer, (13) data output, and (14) sampling train of PAH.

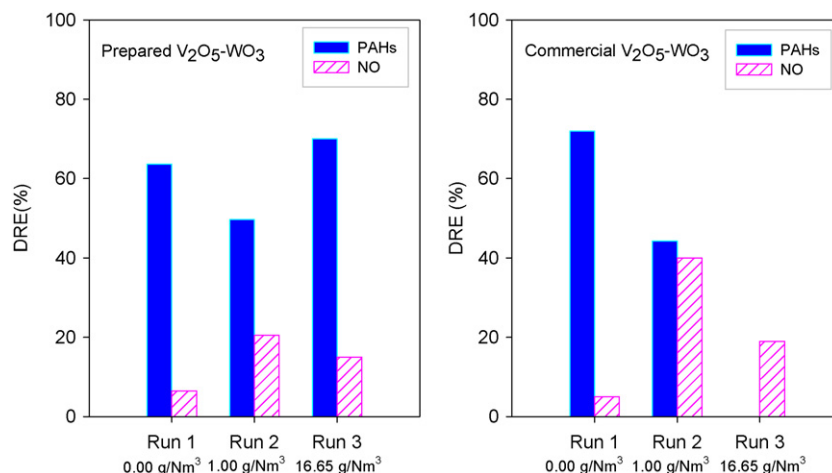
controlled at 6L/min. After the sampling was finished, the XAD-16 adsorbents containing gas-phase PAHs were extracted by a microwave extractor. The extracted solutions were further concentrated to 1 ml by a rotary evaporative concentrator. Finally, the concentrated solutions were stored in brown vials at 4 °C and analyzed by a gas chromatograph/flame ionized detector (GC/FID) (PerkinElmer Autosystem GC). Sixteen compounds of PAHs were analyzed, including Naphthalene (Nap), Acenaphthylene (Acpy), Acenaphthene (Acp), Fluorene (Flu), Phenanthrene (Pha), Anthracene (Ant), Fluoranthene (Flua), Pyrene (Pyr), Benzo(a)anthracene (B(a)A), Chrysene (Chr), Benzo(b)fluoranthene (B(b)F), Benzo(k)fluoranthene (B(k)F), Benzo(a)pyrene (B(a)P), Indeno(1,2,3-cd)pyrene (InP), Dibenzo(a,h)anthracene (DbA), and Benzo(g,h,i)perylene (B(ghi)P). The DRE of total PAHs was defined as  $DRE = (C_1 - C_2)/C_1$ , where  $C_1$  and  $C_2$  are the total concentration of PAHs in the inlet and outlet gases of catalysis reactor, respectively.

The sampling of particulate matters and heavy metals were carried out simultaneously after the sampling of PAHs, according to the standard methods of Taiwan EPA (NIEA A730.70C). The sampling

location, sampling gas flow rate, and sampling time for particulates and heavy metals were the same with those for PAHs. After the sampling processes, the glass-fiber filters were weighted to determine the concentrations of particulates and then digested with the aqua regia in a microwave reactor. The concentrations of heavy metals in the digested solutions were analyzed by an inductively coupled plasma-atomic emission spectroscope (ICP-AES) (PerkinElmer Optima 2100DV).

## 2.5. Catalyst characterization

The micrographs of catalysts were taken by a Scanning Electron Microscopy (SEM) (JEOL JSM-6700F). The accumulations and the sizes of particles on the reacted catalysts were observed from the SEM images. The contents of C, H, and N on the surface of catalysts were carried out by an EA (Elementar vario EL III). The chemical states of metals on the catalysts were determined by an ESCA (ULVAC-PHI, PHI 5000 VersaProbe) with an Al-K $\alpha$  X-ray source at 1486.6 eV.



**Fig. 2.** Effects of particulate concentrations on the DREs of PAHs and NO by prepared and commercial V<sub>2</sub>O<sub>5</sub>-WO<sub>3</sub> catalysts.



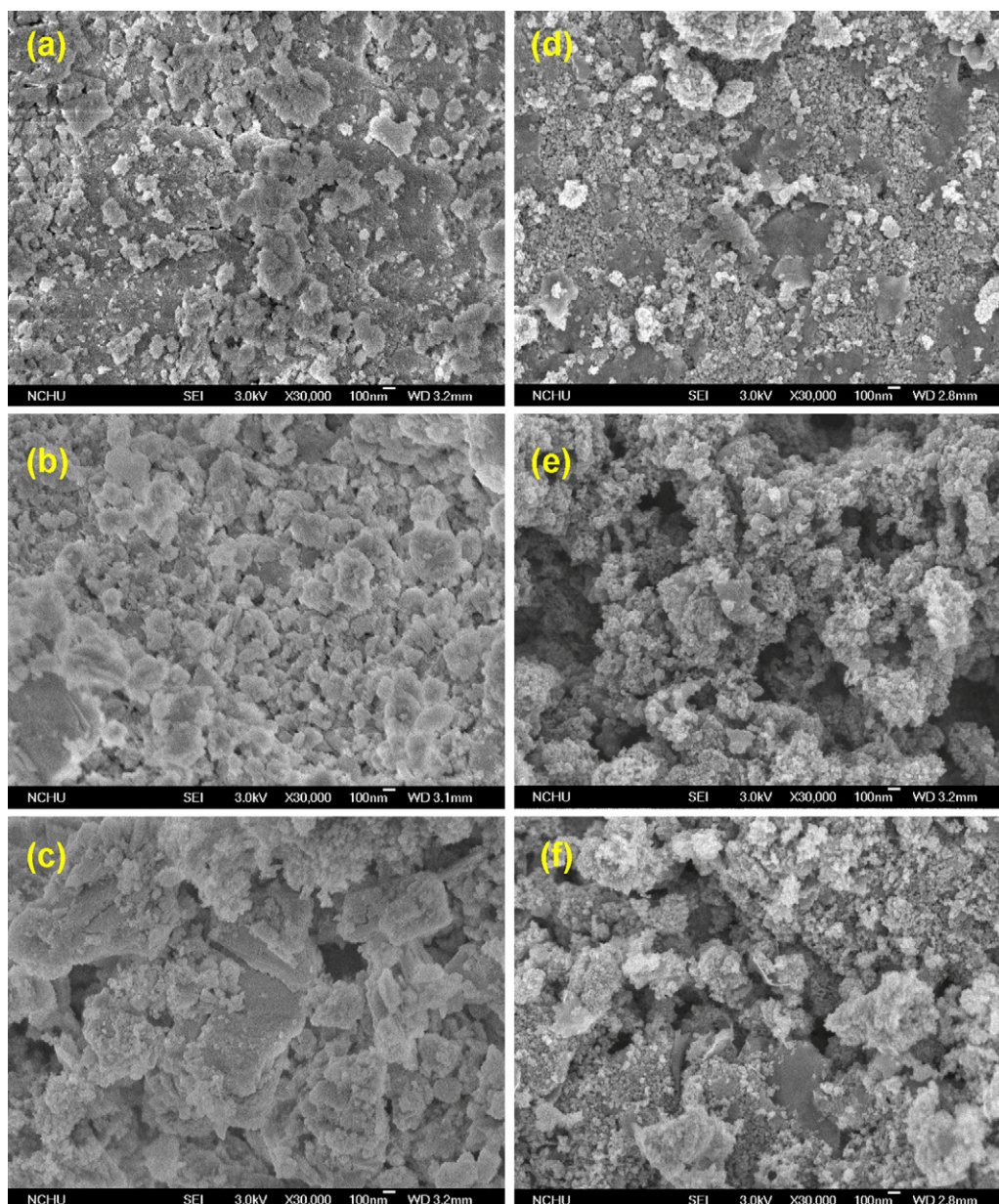


Fig. 3. SEM images: (a) prepared  $V_2O_5-WO_3$  catalyst—Run 1, (b) prepared  $V_2O_5-WO_3$  catalyst—Run 2, (c) prepared  $V_2O_5-WO_3$  catalyst—Run 3, (d) commercial  $V_2O_5-WO_3$  catalyst—Run 1, (e) commercial  $V_2O_5-WO_3$  catalyst—Run 2, (f) commercial  $V_2O_5-WO_3$  catalyst—Run 3.

### 3. Results and discussions

#### 3.1. Effects of particulate matters on the catalysts

Fig. 2 shows the DREs of PAHs and NO by the two catalysts with different concentrations of particulates in the flue gas. When the flue gas did not contain any pollutants (Run 1), the DREs of total

PAHs by prepared and commercial  $V_2O_5-WO_3$  catalysts were 64% and 72%, respectively. However, both two catalysts had low activities for NO abatement because of the deficiency of appropriate reductant. When the flue gas contained  $1.00\text{ g/Nm}^3$  particulates, both the prepared and commercial  $V_2O_5-WO_3$  catalysts had an increased DRE of NO but a decreased DRE of PAHs. When the particulate concentration in the flue gas increased to  $16.65\text{ g/Nm}^3$ , the

Table 2  
Elemental compositions of the catalysts.

Run	Major pollutants	Catalysts	Elemental composition (wt%)		
			C	H	N
2	$1.00\text{ g/Nm}^3$ particulates	Prepared $V_2O_5-WO_3$	0.20/0.19 <sup>a</sup>	0.60/0.56	0.10/0.05
3	$16.65\text{ g/Nm}^3$ particulates	Prepared $V_2O_5-WO_3$	0.10/0.16	0.94/0.98	0.03/0.04
2	$1.00\text{ g/Nm}^3$ particulates	Commercial $V_2O_5-WO_3$	0.40/0.47	0.85/0.75	0.19/0.19
3	$16.65\text{ g/Nm}^3$ particulates	Commercial $V_2O_5-WO_3$	0.21/0.22	0.66/0.56	0.12/0.09

<sup>a</sup> Duplicate analysis results.

DREs of NO and PAHs by commercial catalysts were decreased. The accumulations of particulates on the surface of catalyst can be clearly observed in the SEM images (Fig. 3(a)–(f)). The average size of particulates on the surface of catalysts was 10–50 nm. Some pores and active sites of self-made and commercial  $V_2O_5$ – $WO_3$  catalysts were covered with particulates when the flue gas contained  $1.00\text{ g/Nm}^3$  particulates (Figs. 3(b) and (e)), and this phenomenon was more serious when the particulate concentration increased to  $16.65\text{ g/Nm}^3$  particles (Figs. 3(c) and (f)). To figure out the possible reasons for the influences of particulates on the catalysts, the contents of chemical elements (C, H and N) on the surface of reacted catalysts were analyzed by the elemental analyzer. As shown in Table 2, the weight percentages of C and N in Run 2 were almost two times than that in Run 3. The presences of element N on the surface of catalysts in Runs 2 and 3 can illustrate that NO was adsorbed and decomposed on the catalysts. The promoting effect of particulates on the performance of catalysts for NO conversion is related to the increased carbon content on the surface of catalysts, because the unburned carbon can serve as the reductant for NO conversion, and improve the adsorption of NO as well as the further migrations from particulates to active sites of catalysts [16,17]. On the other hand, the DRE of PAHs by  $V_2O_5$ – $WO_3$  catalysts was influenced by the particle concentration rather than the carbon content. The possible sources of carbon on surface of the catalysts come from the cokes and ash particulates. The former “coke” is formed from the catalytic decomposition of organic compounds, the latter “ash particulate” is formed from the combustion of feedstock. Although the content of carbon on the surface of catalysts was measured, it is difficult to determine the dominated source of carbon. The results show that the carbon contents did not increase with the concentrations of particles. The possible reason can be observed from Fig. 2, the DRE of PAHs was decreased and which resulted in less formation of coke. Therefore, a decrease in carbon content was observed when the concentrations of particulates increased. Furthermore, comparing the results of Runs 2–3 with Run 1 (without particulates) indicate that both  $V_2O_5$ – $WO_3$  catalysts had activities for PAHs and NO removals even with high concentrations of particulates in the flue gas.

### 3.2. Effects of heavy metals on the catalysts

To study the effects of different concentrations of heavy metals (Pb and Cd) on the performances of catalysts, the contents of heavy metals in the feedstock were controlled at 0, 0.5, and 2.0 wt%. Runs 4 and 5 were designed to evaluate the effects of heavy metal Cd, and Runs 6 and 7 were designed to evaluate the effects of heavy metal Pb. The experimental results are shown in Fig. 4. When the content of Cd in the feedstock was increased from 0 to 2.0 wt%, the DREs of total PAHs by prepared and commercial  $V_2O_5$ – $WO_3$  catalysts were decreased from 64% to –26% and from 72% to –122%, respectively. The results indicated that the presence of heavy metal Cd could poison the catalysts and even promote the formations of PAHs [18].

Regarding the effects of heavy metal Pb, the results show that the DREs of total PAHs by prepared and commercial  $V_2O_5$ – $WO_3$  catalysts were decreased as the feedstock contained 0.5 wt% Pb but increased to 85% as the feedstock contained 2.0 wt% Pb. The presence of heavy metal Pb would cover the active sites of catalyst and provide additional catalytic sites for PAHs decomposition.

The effects of heavy metals on the performances of the catalysts were further investigated by ESCA analysis. Table 3 lists the results of ESCA analysis for the prepared and commercial  $V_2O_5$ – $WO_3$  catalysts after activity tests. The possible species on the surface of catalysts were identified from the ESCA database [19]. For the prepared and commercial  $V_2O_5$ – $WO_3$  catalysts in Runs 5 and 7, the binding energies (BE) of V (2d3/2) at 514.8–515.2 eV and W (4f5/2) at 35.2–35.8 eV were assigned to  $V_2O_5$  and  $WO_3$ , respectively. The

**Table 3**  
Results of ESCA analysis for the reacted catalysts.

Catalyst	Deposited content	Binding energy (eV)							
		Al (2p)	Ti (2p3/2)	V (2p3)	W (4f4/2)	Cd (3d5/2)	Pb (4f7/2)	S (2p3/2)	Cl (2p3/2)
Prepared $V_2O_5$ – $WO_3$ (Run 5)	Cd < 0.1%	74.3 [ $\gamma$ - $Al_2O_3$ ]		514.8 [ $V_2O_5$ ]	35.8 [ $WO_3$ ]	404.2 [CdO] 405.2 [Cd(OH) <sub>2</sub> ]			
Prepared $V_2O_5$ – $WO_3$ (Run 7)	Pb = 0.2%	74.1 [ $\gamma$ - $Al_2O_3$ ]		515.2 [ $V_2O_5$ ]	35.5 [ $WO_3$ ]		138.0 [PbO]		
Prepared $V_2O_5$ – $WO_3$ (Run 11)	Cd < 0.1% Pb < 0.1%	74.1 [ $\gamma$ - $Al_2O_3$ ]		515.3 [ $V_2O_5$ ]	35.7 [ $WO_3$ ]	405.0 [Cd(OH) <sub>2</sub> ] 405.6 [CdCl <sub>2</sub> ]	140.2 [PbSO <sub>4</sub> ]	169.2 [SO <sub>4</sub> <sup>2-</sup> ]	198.7 [CdCl <sub>2</sub> ]
Commercial $V_2O_5$ – $WO_3$ (Run 5)	Cd < 0.1%		458.2 [TiO <sub>2</sub> ]	514.9 [ $V_2O_5$ ]	35.2 [ $WO_3$ ]	404.0 [CdO] 404.8 [Cd(OH) <sub>2</sub> ]			
Commercial $V_2O_5$ – $WO_3$ (Run 7)	Pb = 0.2%		458.2 [TiO <sub>2</sub> ]	514.9 [ $V_2O_5$ ]	35.4 [ $WO_3$ ]		138.0 [PbO]		
Commercial $V_2O_5$ – $WO_3$ (Run 11)	Cd < 0.1% Pb < 0.1%		458.2 [TiO <sub>2</sub> ]	514.9 [ $V_2O_5$ ]	35.2 [ $WO_3$ ]	404.0 [CdO] 406.1 [CdCl <sub>2</sub> ]	139.8 [PbSO <sub>4</sub> ]	168.3 [SO <sub>4</sub> <sup>2-</sup> ]	198.6 [CdCl <sub>2</sub> ]

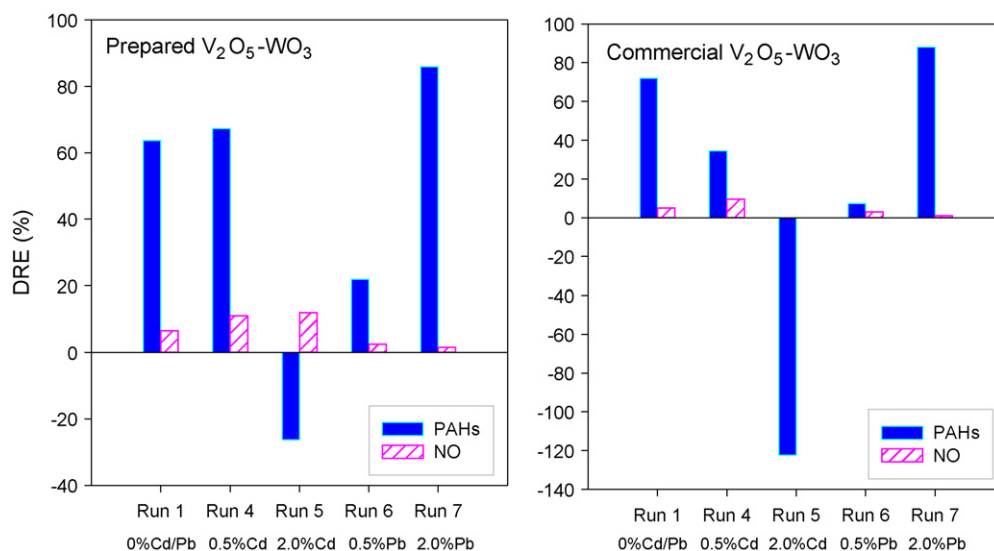


Fig. 4. Effects of heavy metal concentrations on the DREs of PAHs and NO by prepared and commercial  $V_2O_5-WO_3$  catalysts.

results indicated that the chemical states of V and W on the catalysts were not influenced by the heavy metals Cd and Pb. The BE of Al (2p) for prepared  $V_2O_5-WO_3$  catalyst was attributed to  $\gamma-Al_2O_3$ . The BE of Ti (2p3/2) for commercial  $V_2O_5-WO_3$  catalyst was attributed to  $TiO_2$ . These results indicated that the supports of prepared and commercial  $V_2O_5-WO_3$  catalysts did not react with heavy metals Cd and Pb. Table 3 also indicates that the major species of heavy metal Cd emitted from the incineration system were CdO and Cd(OH)<sub>2</sub> when the feedstock contained 2.0 wt% Cd (Run 5), and the major species of heavy metal Pb were PbO when the feedstock contained 2.0 wt% Pb (Run 7). Heavy metals in the feedstock were heated and transferred to metal vapors or gaseous compounds at high temperature, and they may flow into the catalysis reactor to block the surface of catalysts [15]. Furthermore, the amount of heavy metal deposited on the surface of catalysts can be checked by ESCA analysis. In Runs 7 and 11, the amount of Pb atom were 0.2% and <0.1%, respectively. These results demonstrate that the feedstock contained high concentration of Pb would lead more deposition of Pb on the catalyst. The deposited Pb would provide the catalytic sites to promote the decomposition of PAHs and thus led to an increase in the DRE of PAHs [14,20]. Furthermore, comparing the results of Runs 4–7 with Run 1 (without heavy metals) indicates that both Cd and Pb had no significant effects on the performances of catalysts for NO removal.

### 3.3. Effects of acid gases on the catalysts

Fig. 5 shows the DREs of PAHs and NO by the catalysts under the presences of different acid gases. The effects of single gas ( $SO_2$  and HCl) and the mix were taken into account. For prepared  $V_2O_5-WO_3$  catalyst, the DREs of total PAHs was -6%, 33% and 37% in Runs 8, 9 and 10, respectively. For commercial  $V_2O_5-WO_3$  catalyst, the DRE of total PAHs was 7%, 27% and 41% in Runs 8, 9 and 10, respectively. According to the results in Run 8, the DREs of total PAHs by prepared and commercial  $V_2O_5-WO_3$  catalysts were significantly suppressed by  $SO_2$ . The result is supported by previous work [21], we found that the presence of  $SO_2$  could react with active sites of the catalysts and even promote the formations of PAHs. Above results indicate that the activities of both two catalysts for PAHs removal were significantly deactivated by  $SO_2$  but the suppression effect of  $SO_2$  was mitigated as HCl was co-existed in the flue gas. This phenomenon may be attributed to the competitive absorption between the  $SO_2$  and HCl gases on the active sites of catalysts. Liu

et al. [22] also reported that the removal of low-ring PAHs with  $SO_2$  present in the flue gas was increased with the presence of HCl, which was attributed to the higher absorption strength of HCl on the surface of catalysts than that of  $SO_2$ . The suppression effect of  $SO_2$  was decreased as HCl co-existed in the flue gas. Comparing the results of Runs 8–10 with run 1 (without acid gas), both HCl and

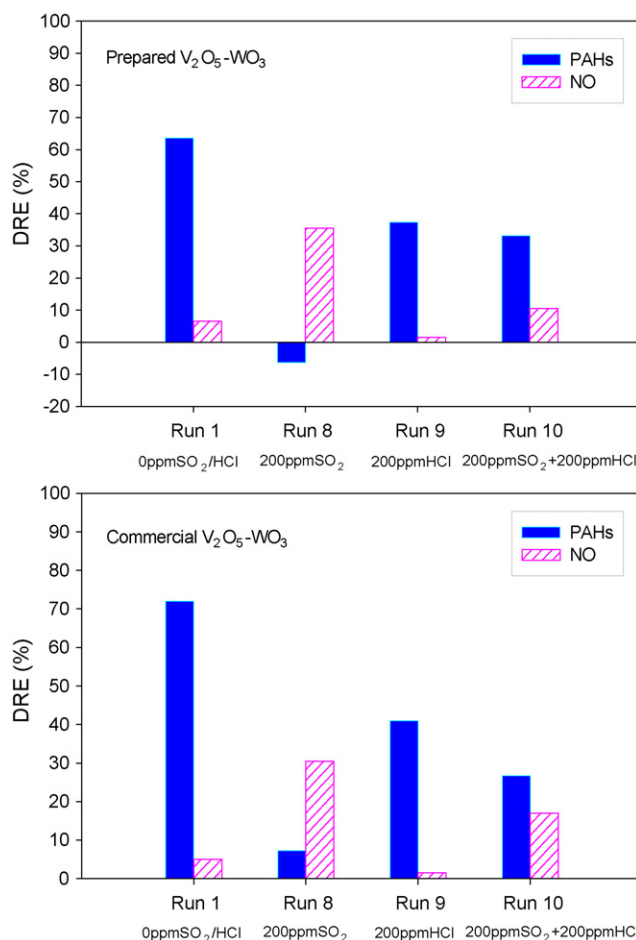
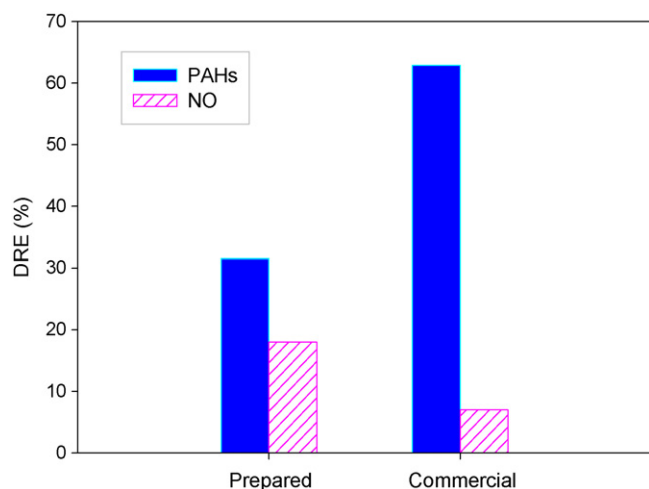


Fig. 5. Effects of acid gas on the DREs of PAHs and NO by prepared and commercial  $V_2O_5-WO_3$  catalysts.





**Fig. 6.** Effects of multiple pollutants (0.5 wt% Cd, 0.5 wt% Pb, 200 ppm SO<sub>2</sub> and 200 ppm HCl) on the DREs of PAHs and NO by prepared and commercial V<sub>2</sub>O<sub>5</sub>-WO<sub>3</sub> catalysts.

SO<sub>2</sub> had negative effects on the performances of catalysts for PAHs removal. The influence level of SO<sub>2</sub> was higher than HCl.

On the other hand, the conversions of NO by prepared and commercial V<sub>2</sub>O<sub>5</sub>-WO<sub>3</sub> catalysts were increased to 35% and 31%, respectively as SO<sub>2</sub> was present in the flue gas. This result is consistent with previous studies [9,10], which also addressed that the catalytic activity of V<sub>2</sub>O<sub>5</sub>-WO<sub>3</sub> catalysts for NO reduction could be promoted by SO<sub>2</sub>. Comparing the results of Runs 1 and 9, the NO conversion was significantly reduced when the flue gas contained 200 ppm HCl. HCl could strongly adsorb on the surface of catalysts and react with the active metals or the supports to form metal-chlorides [14,15]. However, the suppression effect of HCl was mitigated as SO<sub>2</sub> co-existed in the flue gas. The influence level of HCl on the performances of the catalysts for NO removal was higher than SO<sub>2</sub>.

#### 3.4. Effects of multiple pollutants on the catalysts

Fig. 6 also shows the DREs of PAHs and NO by the catalysts as the flue gas contained multiple pollutants, including heavy metals (Cd and Pb) and acid gases (SO<sub>2</sub> and HCl) (Run 11). The DREs of total PAHs were 32% and 63% for prepared and commercial V<sub>2</sub>O<sub>5</sub>-WO<sub>3</sub> catalysts, respectively. Both catalysts had low activities for NO removal but were higher than that without these pollutants. From the results of ESCA analyses (Table 3), the presences of heavy metals, SO<sub>2</sub>, and HCl on the surface of V<sub>2</sub>O<sub>5</sub>-WO<sub>3</sub> catalysts did not change the chemical states of V and W. The major species formed on the surface of catalysts were CdCl<sub>2</sub> and PbSO<sub>4</sub>, they had negative effects on the performance of V<sub>2</sub>O<sub>5</sub>-WO<sub>3</sub> catalysts. Comparing the results of Run 11 with Run 1, the coexistence of multiple pollutants decreased the DRE of PAHs but increased the NO conversions. The effects of particles, heavy metals, SO<sub>2</sub>, and HCl on the performances of prepared and commercial V<sub>2</sub>O<sub>5</sub>-WO<sub>3</sub> catalysts had similar trends.

#### 4. Conclusion

The activities of prepared and commercial V<sub>2</sub>O<sub>5</sub>-WO<sub>3</sub> catalysts for PAHs and NO removal were practically tested in a laboratory-scale waste incineration system. The effects of particulates, heavy metals, and acid gases on the catalysts were investigated. Based on the results, the following conclusions were obtained:

- Both two catalysts had good catalytic activities for PAHs removal in the waste incineration processes. The DREs of PAHs by prepared and commercial V<sub>2</sub>O<sub>5</sub>-WO<sub>3</sub> catalysts were 64% and 72%, respectively.
- The increases in the particulate concentrations in the flue gas suppressed the DRE of PAHs, but the increases in the carbon content on surface of catalysts promote the NO conversions.
- The DRE of PAHs by the catalysts was significantly suppressed by the increased concentrations of heavy metal Cd, but was promoted with high concentration of Pb.
- The influence level of SO<sub>2</sub> was higher than HCl on the performances of V<sub>2</sub>O<sub>5</sub>-WO<sub>3</sub> catalysts for PAHs removal, but was lower than HCl for NO removal.
- The results of ESCA analysis reveal that the presences of heavy metals, SO<sub>2</sub> and HCl on the surface of catalysts did not change the chemical states of V and W.

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