



Emissions of NO_x, PM, SO₂, and VOCs from Coal-fired Boilers Related to Coal Washing, Iron-steel Production, and Lime and Gypsum Making in Shanxi, China

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ABSTRACT

The accurate pollutant inventories are important for the development of pollution control policies, which further rely on detailed emission factors (EFs) to some extent. However, detailed air pollutant EFs for coal-fired boilers (CFBs) associated with coal washing (CW), iron-steel production (IS), and lime and gypsum manufacturing (LG) are lacking in China at present. CFBs of 91 enterprises involving CW, IS, and LG were investigated to obtain their pollutant EFs associated with coal consumption (EF_I, kg t⁻¹), outputs (EF_{II}, kg MY⁻¹), and product yields (EF_{III}, kg t⁻¹) through field investigation and sampling. The weak correlation between EFs of 4 air pollutants vs. corresponding removal efficiencies (REs), and EFs vs. coal compositions among three industries implied the impact of actual combustion conditions and operating status of removal facilities (RFs). EFs of VOCs from small-scale CW enterprises (SSEs) were much higher than those of large- and medium-scale enterprises (LSEs and MSEs) owing to the incomplete combustion of coal. Also the SO₂ and NO_x EFs of CW increased with decreasing enterprise scale, while the maximum PM occurred at MSEs. The mean EF_I values of LG for the 4 air pollutants was PM > NO_x > VOCs > SO₂, differed from PM > SO₂ > NO_x for the IS, VOCs > PM > NO_x > SO₂ for the CW LSEs and MSEs, and VOCs > NO_x > PM > SO₂ for the CW SSEs, which suggested the influence of combined factors including coal composition, production processes, combustion conditions, and pollutant removal technologies and removal efficiencies. EF_I values for the 8 IS factories followed the order PM > SO₂ > NO_x, while they were PM > NO_x > SO₂ for EF_{II} values due to their output fluctuation. For the EF_{II} and EF_{III} values of SO₂, NO_x, and PM, LG dominated within the 3 industries, while the corresponding maximum VOCs occurred at the CW industry.

Keywords: Emission factor; Coal washing; Lime-gypsum making; SO₂; NO_x; VOCs.

INTRODUCTION

With rapid economic development and urbanization, air pollution has become an increasingly serious issue in China. The severe regional air pollution is mostly characterized by high concentration of fine particulate matter happened frequently in recent China (Hu *et al.*, 2017). Serious haze episodes have occurred in recent Southeast Asia, degrading the air quality in this region including China, Malaysia, and Thailand (Sharma and Balasubramanian, 2018). Particulate matter (PM) had been always a topic of general interest in air pollution issue in China, which has received more and more concerns from Chinese people and government (Lang *et al.*, 2017; Li *et al.*, 2017, 2018). In present China, PM,

SO₂, NO_x, and VOCs originated from different industries are widely recognized as primary air pollutants, which can damage the environment, climate, and human health if they enter into the respiratory and vascular systems of the human body (Yan *et al.*, 2017; Hu *et al.*, 2018; Liu *et al.*, 2018; Zhao *et al.*, 2018). Secondary inorganic aerosol (SIA, sum of sulfate, nitrate, and ammonium) is the main component of PM mainly formed through gaseous pollutant (SO₂, NO_x, and NH₃) to particle conversion, and these gaseous pollutants are emitted from complicated anthropogenic sources including coal and biomass burning, cooking, and traffic-related and industrial emissions (Huang *et al.*, 2014; Lee, 2015). Organic aerosol (OA) contains 100 chemical species and contributes high mass fraction of 20–90% to PM, which is mainly formed through photo-chemical reactions of organic pollutants (VOCs etc.) from anthropogenic combustion sources (Turpin *et al.*, 2000; Carlton *et al.*, 2009). VOCs in ambient air are receiving more and more concern ascribe to many of them have been identified to be human carcinogens, and precursors of both secondary

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organic aerosols and O₃ (Zhang *et al.*, 2015; Hu *et al.*, 2018; Khan *et al.*, 2018).

Coal burning is an important source of aerosol and gaseous pollutants, and impetus for haze formation (Li *et al.*, 2017; Liu *et al.*, 2017; Li *et al.*, 2018; Hu *et al.*, 2019). PM originates from coal combustion contain organic compounds, black carbon (BC), inorganic ions (SO₄²⁻, NO₃⁻, Cl⁻, and NH₄⁺ etc.), and trace metals, which can lead to visibility deterioration, damage ecosystems and human health, and affect climate change substantially, which has attracted widespread attention (Bruns *et al.*, 2015; Hu *et al.*, 2017; Jayarathne *et al.*, 2018; Masekameni *et al.*, 2018). During coal burning process, sulfur contained in coal enters into atmosphere in the forms of SO₂, SO₃, and SO₄²⁻ etc., the main forms lie in combustion residues are FeS₂, CaSO₄, FeSO₄, and ZnS etc. (Hussain and Luo, 2019). The tremendous emissions of SO₂ from coal burning can promote the sulfate aerosols and acid rain, which can result in the destruction of infrastructure and plant growth, and the formation of PM and haze (Saidur *et al.*, 2011). In addition, gaseous emissions from combustion of coal also include CO₂, CO, NO_x, CH₄, VOCs, and inorganic acid (Stockwell *et al.*, 2015; Goetz *et al.*, 2018).

Shanxi and Inner Mongolia are two predominant coal districts in China, whose coal production accounts for 49.2% and 51% of China's total output in 2016 and 2017, respectively. The coal goaf area of Shanxi is as high as 20,000 km², accounting for one seventh of its total area of 15 km² (Niu *et al.*, 2006). A large number of coal related enterprises including coal mining and washing, iron-steel production, and lime and gypsum making cluster in Shanxi Province of China (Li *et al.*, 2018). Coal washing (CW) processes including heavy medium separation, jigging processes, and flotation separation and so on for the reduction of noncombustible minerals, acid precursors of sulfur-bearing minerals, and hazardous trace elements to produce high energy content fuels (Wen, 2000). CW can eliminate coal containing 50–80% ash, and 30–40% of total sulfur, and further achieve substantial cuts of air pollutants emitted from coal burning. Washing of 1 × 10⁸ t coal can reduce the emission of 6–7 × 10⁵ t SO₂, and 1.61 × 10⁷ t of coal gangue. In addition to the reduction of air pollutant emissions, improvement of coal utilization efficiency and conservation of energy were also obtained. Although the coal washing capacity of China is top ranking, the washing coal accounted only 22% of the total coal consumptions (Tang *et al.*, 2005; Gu *et al.*, 2012). China is the largest country in iron steel producing and consuming. Crude steel production in China was 717 million metric tons in 2012, which accounted for 46% of the world's production (WSA, 2013). The emission amounts of PM and SO₂ from iron-steel enterprises contributed 26.2% and 13.3% to the correspondingly Chinese industrial PM and SO₂ emissions (Yan *et al.*, 2015). Gypsum used in building industry was obtained through calcining of dihydrate natural gypsum or chemical gypsum at a certain temperature and subsequently dehydrated and decomposed to hemihydrates gypsum. More than 90% of lime and gypsum in China were linked with construction industry,

and the industry associated with cement-, lime-, and gypsum-production contributes 0.73% to Chinese GDP in 2007.

Huge quantities of coal burned in coal fired boilers were needed to provide heating and vapor for the production processes in CW, IFP, and LG industries, and large amounts of SO₂, NO_x, PM, and VOCs are released. To our knowledge, few studies were conducted focus on emissions of coal fired boilers applied in these 3 types of industries.

Improved emission inventories (EIs) combined with detailed source information, in terms of emission factors and rate, and spatial distribution of sources, are imperative for better understanding of the sources and the formation mechanism of serious air pollution, and subsequently effective pollution control policies development (Zhou *et al.*, 2017; Horák *et al.*, 2018; Yue *et al.*, 2018; Zheng *et al.*, 2019). However, gigantic uncertainty existed in EIs establishment using poorly constrained global or regional models, so the detailed EFs specific to industry size or different industries were urgently need to obtain the accurate EIs (Li *et al.*, 2018; Horák *et al.*, 2018; Hu *et al.*, 2019).

In this study, a total of 91 enterprises related to coal washing, iron-steel production, and lime and gypsum making were investigated. Field sampling and subsequent laboratory measured to obtain the information about their annual outputs, product yields, pollutant removal efficiencies, coal compositions, and pollutant concentrations in flue gas. All of these works aimed to achieve the following goals: 1) acquisition of localized EFs associated with SO₂, PM, NO_x, and VOCs for these enterprises; 2) obtainment of three expressions of EFs associated with coal consumption, output, and product yield to improve their practicability.

MATERIALS AND METHODS

Field Investigation of the Related Companies

In this study, 91 companies in Shanxi Province involving 79 coal washing enterprises, 8 iron-steel factories, and 4 lime and gypsum production plants were on-site investigated for their production and coal related information in 2017. SO₂, PM, and NO_x were real-time monitored using a flue gas analyzer, while VOCs in flue gas were sampled and subsequently analyzed by a GC-MS system.

Tables 1–3 listed the statistics including product types and yields, output, and fuel coal compositions in boilers for 79 CW enterprises involving 19 large-scale enterprises (LSEs), 37 medium-scale enterprises (MSEs), and 23 small-scale enterprises (SSEs). The corresponding statistic values for 8 iron-steel (IS) factories, and 4 lime and gypsum (LG) making plants were also provided in Tables 4 and 5, respectively. It should be pointed that the scale of enterprise was designated based on the initially designed product yield and output, not that the actual yield under the actually annual running time.

It is worth noting that all the 91 enterprises were not equipped with VOC removal facilities (RFs). NO_x RFs were installed in a small number of factories, while PM RFs were installed in all the 91 factories.

Table 1. Statistical values for large scale coal washing enterprises.

	Output (MY)	CC (kt a)	S _{ad} (%)	A _{ad} (%)	Product	Yield (kt)	SO ₂ RE (%)	NO _x RE (%)	PM RE (%)	VOCs RE (%)
F1	2570	27.8	0.33	17.6	raw coal	8070	55.3	0.00	92.9	0.00
F2	1460	30	0.31	23.0	raw coal	37.7	11.8	0.00	86.2	0.00
F3	1040	7.58	0.30	12.3	raw coal	2200	53.5	36.5	95.6	0.00
F4	1310	0.32	0.30	21.4	raw coal	2620	62.5	0.00	76.6	0.00
F5	3240	39.4	0.31	15.0	raw coal	6850	53.6	0.00	95.1	0.00
F6	46.9	1.50	0.50	12.6	raw coal	160	0.00	0.00	0.00	0.00
F7	1130	13.5	0.34	22.0	raw coal	2620	52.2	0.00	98.0	0.00
F8	3160	7.20	0.30	15.8	raw coal	7130	76.7	0.00	63.7	0.00
F9	3000	36.3	0.30	23.0	raw coal	7050	79.4	0.00	88.8	0.00
F10	341	2.95	0.35	19.6	raw coal	1430	53.0	40.0	92.8	0.00
F11	659	2.82	0.32	16.9	raw coal	1490	6.30	12.5	94.9	0.00
F12	428	4.92	0.75	17.1	raw coal	1040	51.5	56.8	82.8	0.00
F13	4250	20.1	0.40	14.0	raw coal	7500	58.7	41.0	92.7	0.00
F14	1830	12.2	0.33	20.5	raw coal	4000	53.4	4.00	92.3	0.00
F15	447	1.00	1.40	17.0	raw coal	1210	65.0	0.00	87.1	0.00
F16	241	2.11	1.99	19.0	raw coal	735	70.0	0.00	87.1	0.00
F17	273	1.80	1.40	17.0	raw coal	1120	65.0	0.00	87.1	0.00
F18	137	1.50	1.60	17.0	raw coal	645	65.0	0.00	87.1	0.00
F19	231	1.35	0.90	14.0	raw coal	623	0.00	0.00	66.7	0.00

Sampling and Measurement of SO₂, NO_x, and PM

The same method for sampling and measurement of SO₂, NO_x (sum of NO and NO₂), and PM (particles with all size in flue gas) detailed described in Li *et al.* (2018) and Hu *et al.* (2019) was adopted in this study.

The gaseous pollutants SO₂, NO_x and CO originated from the coal fired boilers applied in all the enterprises were monitored online by a flue gas analyzer (Laoying-3012H, Qingdao LaoYing Environmental Science and Technology, Co., Ltd.) placed at outlet channel of flue gas after RFs to get the information related to pollutants actually released into atmosphere. The additional parameters such as temperature and flow velocity (m s⁻¹) of flue gas were also measured and provided by this gas analyzer. PM was also sampled by this analyzer and the collected mass divided by the corresponding sampling volume of flue gas was used to represent PM concentration. The analyzer was calibrated with zero gas and standard gases (NO_x, SO₂ and O₂) before measurement for the elimination of possible interferences. The mass emissions of SO₂, NO_x, and VOCs were calculated as their concentrations multiplied by sampling volumes of flue gas.

Two pathways including request from enterprises and field sampling and subsequent laboratory measurement were used to obtain the information about coal components for all the enterprises. The proximate- and ultimate-analysis of fuel coal burned in coal-fired boilers referred to the Chinese standards of GB/T-212-2008 and GB/T 476-2001, which aimed to the data acquisition associated with contents of ash, sulfur, carbon, hydrogen, nitrogen, oxygen, and water.

VOCs Sampling and Analysis

VOCs sampling and analysis were conducted based on the standard method designated by Chinese Ministry of

Environmental Protection (HJ 734-2014) for smoke containing VOCs derived from stationary sources. The sampling and analysis procedures of VOCs were divided to 3 steps: adsorption using a stainless pipe used in TD-100 system (Markes International, UK), VOCs thermal desorption by TD-100, and detection by a HP6890 GC/5973i MS system. The adsorption tubes installed at the outlet of the sampling gun (lasted 5 mins at a flow rate of 40 mL min⁻¹) were applied to the VOCs sampling. The interference from water was eliminated through condensation using an ice bath impact bottle before adsorption pipe. VOCs sample pretreatment and analysis methods were all subordinated to Hu *et al.* (2019). The calibration standards were prepared by diluting 100 ppbv of PAMS (Photochemical Assessment Monitoring Station, USA) (Yan *et al.*, 2016; Widiana *et al.*, 2017). The sum of 57 VOC species was used to represent total VOCs in this study.

The quality assurance and quality control measures were detailed described in Hu *et al.* (2019). Detection within 24 h, penetration experiment and activation of the adsorption tube, field blank and instrumental calibration before test were all included in this study. The MDLs were same to the reported values of Hu *et al.* (2019) and listed in Table S1.

Calculation of Emission Factors in Three Expressions

The same calculation methods of EFs described by Li *et al.* (2018) and Hu *et al.* (2019) were adopted in this study. In order to enhance EFs practicability in EIs establishment, coal consumption (EF_I, kg t⁻¹), output (EF_{II} reported in kg MY⁻¹), and product yield (EF_{III}, kg t⁻¹) associated EFs were provided and calculated using the Eqs. (1)–(3).

$$EF_I \text{ (kg t}^{-1}\text{)} = C \text{ (kg m}^{-3}\text{)} \times V_{FA} \text{ (m}^3 \text{ kg}^{-1}\text{)} \times 1000 \text{ kg t}^{-1} \quad (1)$$

where C is mass concentrations of gaseous pollutants, V_{FA} is

Table 2. Statistical values for medium scale coal washing enterprises.

	Output (MY)	CC (kt)	S _{ad} (%)	A _{ad} (%)	Product	Yield (kt)	SO ₂ RE (%)	NO _x RE (%)	PM RE (%)	VOCs RE (%)
F20	302	2.30	0.27	15.5	raw coal	600	62.5	0.00	99.4	0.00
F21	64.0	3.20	0.30	17.0	raw coal	900	25.0	0.00	99.0	0.00
F22	380	5.80	0.38	17.9	raw coal	920	84.8	0.00	99.0	0.00
F23	90	3.00	0.35	16.2	raw coal	200	89.3	0.00	99.0	0.00
F24	80	2.70	0.45	17.0	raw coal	300	0.00	0.00	99.0	0.00
F25	70	2.10	0.30	16.0	raw coal	260	65.8	0.00	98.9	0.00
F26	108	3.60	0.30	17.0	raw coal	327	80.6	0.00	98.9	0.00
F27	184	3.80	0.30	11.0	raw coal	460	38.1	0.00	98.9	0.00
F28	1190	9.60	0.28	14.0	raw coal	2400	73.8	0.00	99.0	0.00
F29	120	1.68	0.31	17.0	raw coal	350	27.7	0.00	97.0	0.00
F30	78.0	0.70	0.35	15.0	raw coal	150	0.00	0.00	98.9	0.00
F31	71.0	3.00	0.60	12.3	raw coal	173	82.9	0.00	98.9	0.00
F32	30.6	1.10	0.30	15.0	raw coal	320	0.00	0.00	99.0	0.00
F33	200	0.95	0.50	16.0	raw coal	420	0.00	0.00	98.9	0.00
F34	132	0.90	0.30	17.0	raw coal	420	30.3	0.00	99.0	0.00
F35	1480	14.8	0.37	18.0	raw coal	3370	67.8	59.5	20.8	0.00
F36	469	4.83	0.39	20.0	raw coal	1400	9.50	0.00	4.60	0.00
F37	37.5	0.88	0.38	12.5	raw coal	75.0	10.6	0.00	10.0	0.00
F38	750	7.34	0.31	12.2	raw coal	900	57.5	0.00	91.6	0.00
F39	203	0.85	0.30	13.0	raw coal	1090	40.0	0.00	30.4	0.00
F40	258	3.08	0.34	14.0	raw coal	750	10.3	15.0	9.40	0.00
F41	306	4.30	0.30	15.0	raw coal	1050	45.4	0.00	34.8	0.00
F42	477	1.85	0.40	11.8	raw coal	1200	10.0	0.00	10.0	0.00
F43	98.1	3.42	0.49	13.2	raw coal	200	42.5	0.00	87.3	0.00
F44	200	1.70	2.79	28.6	raw coal	500	65.0	0.00	87.1	0.00
F45	186	5.20	2.50	11.0	raw coal	818	65.0	0.00	87.2	0.00
F46	7.27	0.16	1.40	17.0	raw coal	18.5	70.0	0.00	87.1	0.00
F47	25.2	4.16	1.00	23.1	raw coal	40.2	78.8	0.00	95.0	0.00
F48	242	4.20	2.50	15.0	raw coal	1050	0.00	0.00	50.8	0.00
F49	253	0.80	1.10	17.0	raw coal	446	0.00	0.00	76.4	0.00
F50	257	4.50	0.80	13.0	raw coal	824	0.00	0.00	0.00	0.00
F51	20.1	4.35	1.42	10.1	raw coal	740	66.2	0.00	47.6	0.00
F52	184	3.80	0.86	15.8	raw coal	455	81.4	0.00	80.0	0.00
F53	67.6	0.85	0.41	13.8	raw coal	315	35.9	0.00	68.3	0.00
F54	238	2.99	0.49	17.5	raw coal	790	72.3	0.00	54.1	0.00
F55	191	1.60	1.33	18.0	clean coal	538	0.00	0.00	0.00	0.00
F56	172	1.72	0.50	18.0	raw coal	541	70.0	0.00	87.2	0.00

the actual flue gas volume derives from 1 kg coal burning, which can be induced by V_{AT} .

$$EF_{II} (\text{kg MY}^{-1}) = (C (\text{kg m}^{-3}) \times 1000 (\text{kg t}^{-1}) \times V_{FA} (\text{m}^3 \text{kg}^{-1}) \times \text{Coal consumption} (\text{t a}^{-1})) / \text{Output} (\text{MY a}^{-1}) \quad (2)$$

$$EF_{III} (\text{kg t}^{-1}) = (C (\text{kg m}^{-3}) \times 1000 (\text{kg t}^{-1}) \times V_{FA} (\text{m}^3 \text{kg}^{-1}) \times \text{Coal consumption} (\text{t a}^{-1})) / \text{Product yeild} (\text{t a}^{-1}) \quad (3)$$

V_{AT} ($\text{m}^3 \text{kg}^{-1}$) is the theoretical air volume needed by burning of 1 kg of coal and obtained using Eq. (4).

$$V_{AT} = 0.0889\omega(C_{ar}) + 0.2567\omega(H_{ar}) + 0.0333\omega(S_{ar}) + 0.0762\omega(N_{ar}) - 0.0333\omega(O_{ar}) \quad (4)$$

C_{ar} , H_{ar} , O_{ar} , N_{ar} , and S_{ar} are corresponding element contents contained in fuel coal on the received basis.

V_{FT} is theoretically generated flue gas volume from 1 kg coal combustion and calculated by Eq. (5).

$$V_{FT} = V_{CO_2} + V_{SO_2} + V_{NO_2} + V_{N_2} + V_{H_2O} \quad (5)$$

$$V_{CO_2} + V_{SO_2} + V_{NO_2} = 0.01867\omega(C_{ar}) + 0.007\omega(S_{ar}) + 0.0016\omega(N_{ar}) \quad (6)$$

where V_{CO_2} , V_{SO_2} , and V_{NO_2} refer to volumes of CO_2 , SO_2 , and NO_2 derived from burning of C, H, and N in coal, V_{N_2} is the N_2 volume in V_{AT} and equal to $0.79V_{AT}$, and V_{H_2O} is the water vapor volume sum of coal containing H burning ($0.112\omega(H_{ar})$), vaporization of coal containing water ($0.00124\omega(M_{ar})$), and vapor in air ($0.0161V_{AT}$).

Finally, V_{AT} derived from 1 kg coal combustion is calculated by Eq. (7).

Table 3. Statistical values for small scale coal washing enterprises.

	Output (MY)	CC (kt a ⁻¹)	S _{ad} (%)	A _{ad} (%)	Product	Yield (kt)	SO ₂ RE (%)	NO _x RE (%)	PM RE (%)	VOCs RE (%)
F57	55.0	1.20	0.35	16.0	raw coal	190	27.2	0.00	98.9	0.00
F58	80	0.75	0.50	17.0	raw coal	300	0.00	0.00	98.8	0.00
F59	105	0.68	0.51	17.0	raw coal	210	0.00	0.00	98.9	0.00
F60	51.0	1.20	0.34	16.0	raw coal	180	0.00	0.00	99.0	0.00
F61	146	0.73	0.30	14.7	raw coal	21.0	22.1	0.00	99.0	0.00
F62	195	1.20	0.30	14.0	raw coal	697	20.1	0.00	10.0	0.00
F63	13.0	0.23	0.30	13.0	clean coal	14.0	0.00	0.00	0.00	0.00
F64	14.9	0.13	0.35	18.0	clean coal	20.0	0.00	0.00	0.00	0.00
F65	1.62	0.30	0.30	17.0	clean coal	5.40	0.00	0.00	0.00	0.00
F66	278	0.50	0.39	11.8	clean coal	280	0.00	0.00	0.00	0.00
F67	0.21	0.13	0.34	14.0	clean coal	2.80	0.00	0.00	0.00	0.00
F68	37.6	0.53	1.60	17.0	raw coal	164	65.0	0.00	87.1	0.00
F69	52.0	0.30	1.50	17.0	clean coal	91.7	70.0	0.00	87.1	0.00
F70	11.3	0.34	1.50	17.0	clean coal	21.4	70.0	0.00	87.0	0.00
F71	21.0	0.20	1.50	17.0	clean coal	54.0	70.0	0.00	87.1	0.00
F72	71.3	0.28	1.50	17.0	clean coal	195	69.9	0.00	87.1	0.00
F73	180	0.35	1.50	17.0	clean coal	240	70.0	0.00	87.1	0.00
F74	24.4	3.90	0.46	20.2	raw coal	76.0	64.4	0.00	85.7	0.00
F75	20.3	5.00	0.85	16.0	raw coal	261	67.6	0.00	29.1	0.00
F76	36.0	4.10	0.45	20.2	raw coal	150	69.6	16.6	96.9	0.00
F77	189	1.54	0.31	23.0	raw coal	372	50.0	0.00	90.7	0.00
F78	2.09	0.20	2.80	9.00	clean coal	35.0	89.3	67.8	88.9	0.00
F79	2.00	1.20	0.35	18.0	clean coal	42.0	70.1	0.00	87.2	0.00

$$V_{FA} = V_{FT} + (\alpha - 1) V_{AT} + 0.0161(\alpha - 1) V_{AT} \quad (7)$$

where α is the excess air coefficient, which is provided by corresponding enterprise.

RESULTS AND DISCUSSION

Emission Factors of NO_x, VOCs, SO₂, and PM for Boilers in Coal Washing

A total of 79 coal washing enterprises were investigated for their coal consumptions, fuel coal components, outputs, product yields, and large-, medium-, and small-scale enterprises were all involved and the related information was listed in Tables 1–3. Obvious output fluctuation exhibited for 79 enterprises, which ranged from 0.21 to 4250 MY a⁻¹ with the mean value as 463 ± 830 MY a⁻¹. The large-, medium-, and small-coal washing enterprise possessed the mean output value as 1350 ± 1280, 249 ± 305, and 67.0 ± 77.1 MY a⁻¹. The ash contents (air dried basis) of fuel coal were not differed from each other among three scale enterprises, which were in the range of 9.00–28.6% with the mean value as 16.4 ± 3.33%. The sulfur contents also showed no differences among three scale enterprises, they fluctuated from 0.27 to 2.80% with the mean value as 0.71 ± 0.63%. The products of these enterprises contained raw coal and clean coal with their yields ranged from 18.5 to 8070 and from 2.80 to 538 kt a⁻¹, respectively. The annual outputs for all the 79 enterprises were correlated well with their product yields ($R^2 = 0.91$, $p < 0.05$). Generally the coal consumptions were also correlated with the product yields ($R^2 = 0.59$, $p < 0.01$) and output values ($R^2 = 0.66$, p

< 0.05).

Among 79 coal washing enterprises, only 8 ones were not installed with PM RFs, 18 ones were not equipped with SO₂ RFs, while only 10 ones were equipped with NO_x RFs. It should be noted that all the 79 enterprises were not equipped with VOCs RFs. The PM removal efficiencies (REs) ranged from 4.60% to 99.4% ($80.9 \pm 25.3\%$) and were not correlated with output values ($R^2 = 0.02$), which implied the high PM RE technologies were not always adopted by high output enterprises. SO₂ RE values of 60 enterprises with RFs fluctuated from 6.30% to 89.3%, not correlated with output values, were similar to PM RE values. NO_x REs for 10 enterprises equipped with RFs ranged from 4.00% to 67.8%, and high RE values of 59.5% and 67.8% occurred at F35 and F78, which were designated as small-scale and medium-scale enterprises. VOCs RE values for all the 79 enterprises were zero due to the lack of RFs. Double alkali method and SNCR were main NO_x removal technologies involved in these enterprises. The flue gas desulfurization methods contained double alkali, NH₃·H₂O absorption, and limestone gypsum absorption. Also NO_x EFs were not correlated with NO_x REs and N contents in coal, which suggested the formation of thermal-NO_x and impact of the poor operation conditions of NO_x RFs.

The RFs applied in coal washing industries should be further improved when all the present RFs were taken into account.

Figs. 1 and 4 showed the EFs with 3 expressions for 19 coal washing enterprises belong to large-scale enterprises. In generally, EF_I and EF_{II} values showed the similar trends, VOCs possessed the highest EF value, followed by PM >

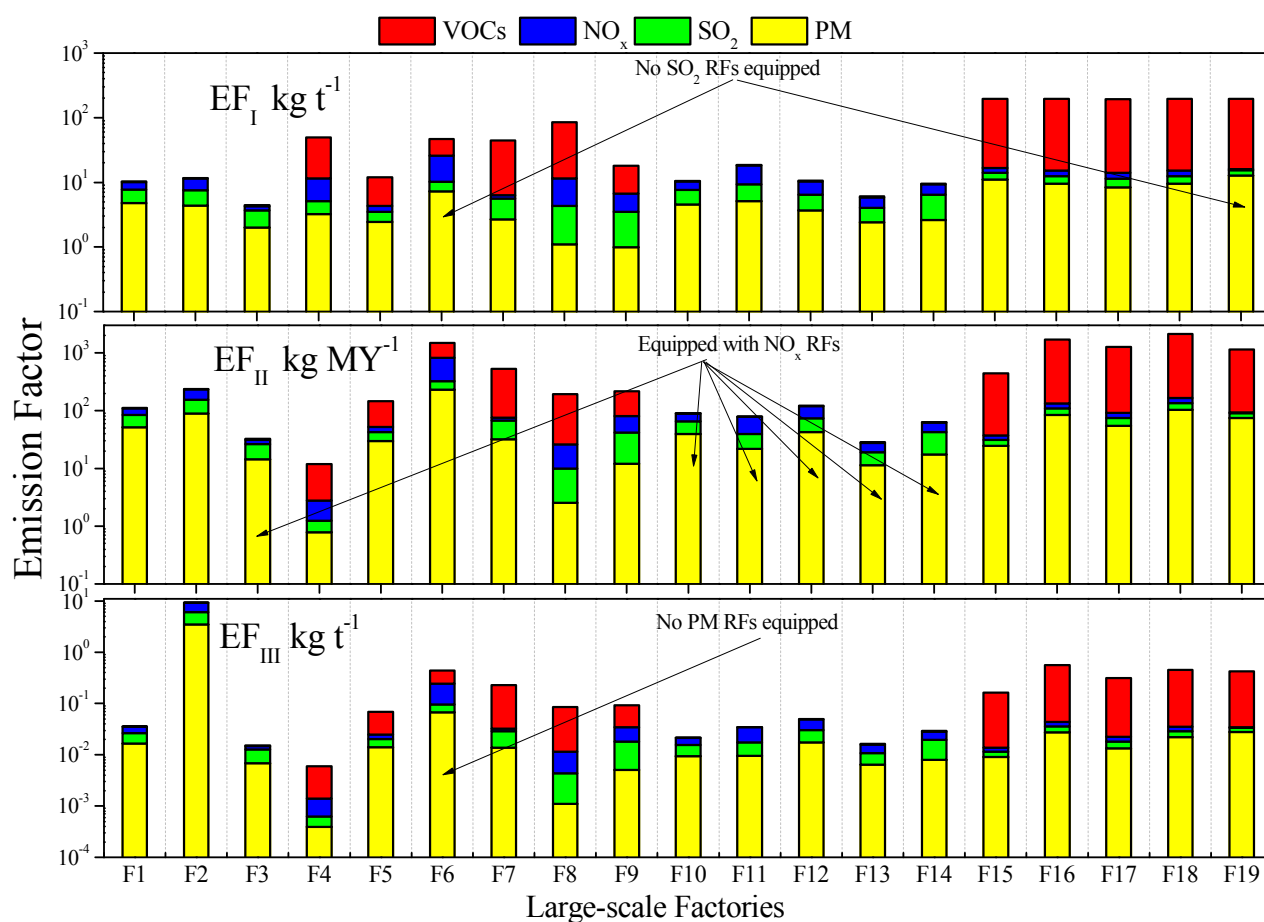


Fig. 1. Emission factors of the coal-fired boilers used in large-scale coal washing enterprises.

$\text{NO}_x > \text{SO}_2$. For EF_I values (in kg t^{-1}), $0.06\text{--}180$ (57.4 ± 75.5), $0.99\text{--}12.8$ (5.17 ± 3.43), $0.44\text{--}15.8$ (3.82 ± 3.56), and $1.06\text{--}4.18$ (2.74 ± 0.721) were attributed to VOCs, PM, NO_x , and SO_2 , respectively. Compared with other 3 air pollutants, SO_2 EF values possessed smaller fluctuation, while Hu *et al.* (2019) reported that NO_x has smaller fluctuation, which could be explained by the fluctuation of RFs. The mean value of SO_2 EF_I of F6, and F19 without SO_2 RFs equipped was 2.80 kg t^{-1} , which was higher than the mean value of 2.73 kg t^{-1} for the rest 17 enterprises. The highest SO_2 EF_I occurred at F11 (4.18 kg t^{-1}), while the lowest value of 1.06 kg t^{-1} occurred at F5. EF_I values of 19 enterprises were better correlated with SO_2 REs ($R = -0.50$) than S_{ad} values ($R = -0.01$), implied greater impact of REs than sulfur contents, which was similar to the reported results by Li *et al.* (2018) and Hu *et al.* (2019). PM EF_I values were weak correlated with PM RFs and A_{ad} values, suggested the impact of combustion conditions and actual operation status of RFs. For NO_x EF_I , 6 LSEs with RFs installed including F3, F10, F11, F12, F13, and F14 possessed the lower mean value of 3.52 kg t^{-1} than that (3.96 kg t^{-1}) of the rest 13 enterprises, suggested the impact of NO_x RFs. Only F6 was not equipped PM RFs, it had higher PM EF_I value of 7.21 kg t^{-1} than the mean value of 5.06 kg t^{-1} for the rest 18 enterprises without PM RFs. VOCs possessed the highest EF_I reflected the no VOCs RFs were installed

in all the 19 LSEs.

Due to the well correlation between output and coal consumption, EF_{II} values (in kg MY^{-1}) for these 79 enterprises exhibited the similar order as VOCs (407 ± 589) $>$ PM (49.4 ± 53.4) $>$ NO_x (47.7 ± 109) $>$ SO_2 (26.1 ± 21.3), which was different with pharmaceuticals- and food-production industries reported by Li *et al.* (2019). Unlike the drastic fluctuation of prices of different medicines and food, the products and prices were consistent with each other for 79 coal washing factories, so EF_I and EF_{II} values showed the similar fluctuation. The EF_{II} values (in kg MY^{-1}) for PM, SO_2 , and NO_x for the enterprises equipped with RFs had lower mean values as 39.3, 22.8, and 23.5 than the corresponding 231, 54.9, and 58.9 for the enterprises without RFs. SO_2 EF_{II} values showed a better correlation with SO_2 REs ($R = -0.45$) than S_{ad} values of fuel coals ($R = -0.09$), which was similar to EF_I values.

Due to the differences of coal washing processes and product yields, EF_{III} values (in kg t^{-1}) of 4 air pollutants for 19 LSEs differentiated from their EF_I and EF_{II} values, they complied with the order of PM (0.20 ± 0.77) $>$ NO_x (0.18 ± 0.70) $>$ SO_2 (0.14 ± 0.56) $>$ VOCs (0.13 ± 0.16).

In this study, a total of 37 medium scale enterprises associated with coal washing were investigated and field measured. Considering the pollutant RFs, only 2 of 37 MSEs were equipped with NO_x RFs with REs as 59.5% and

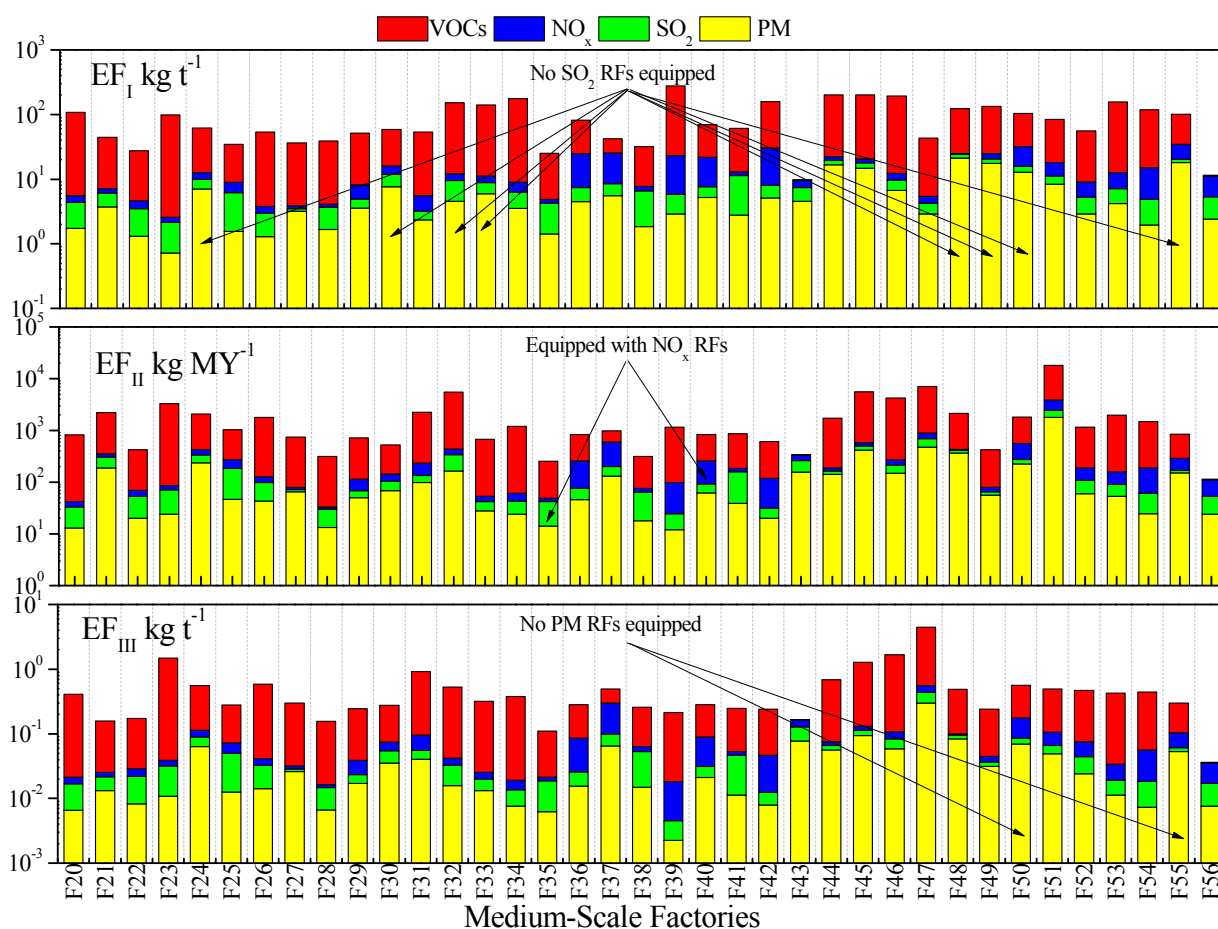


Fig. 2. Emission factors of the coal-fired boilers used in medium-scale coal washing enterprises.

15.0%, 8 MSEs were not equipped with SO_2 RFs, and all the 37 MSEs were not installed with VOCs RFs and were equipped with PM RFs. Figs. 2 and 4 listed the EFs and mean values of EFs for each MSE and 37 MSEs. The output values of 37 enterprises were well correlated with their product yields ($R = 0.92$, $p < 0.01$). EF_I , EF_{II} , and EF_{III} values of 4 air pollutants for 37 MSEs were consistent with EF_I and EF_{II} values of LSEs, which were subordinated to the order as VOCs (78.3 ± 59.1) > PM (5.78 ± 5.29) > NO_x (5.37 ± 6.02) > SO_2 (2.87 ± 1.34) for EF_I (in kg t^{-1}), VOCs (1740 ± 2560) > PM (149 ± 297) > NO_x (113 ± 236) > SO_2 (70.3 ± 106) for EF_{II} (in kg MY^{-1}), while they were VOCs (0.45 ± 0.67) > PM (0.04 ± 0.05) > NO_x (0.03 ± 0.04) > SO_2 (0.02 ± 0.02) for EF_{III} (in kg t^{-1}), respectively (Fig. 4). VOCs possessed the overwhelming EF_I , EF_{II} , and EF_{III} values among 4 air pollutants attributed to the uninstalled VOCs RFs in all the 37 MSEs, which ranged from 0.21 kg t^{-1} of F43 to 252 kg t^{-1} of F39, 3.9 kg MY^{-1} of F56 to 14300 kg MY^{-1} of F51, and 1.00×10^{-3} kg t^{-1} of F56 to 1.56 kg t^{-1} of F46 (Fig. 2). The most value of VOCs EF_I , EF_{II} , and EF_{III} occurred at different factories implied the impact of production yield and product prices. PM REs varied from 9.40% to 99.4% for the 35 enterprises owning RFs, the mean value of PM EF_I , EF_{II} , and EF_{III} for these 35 factories were 5.23, 147, and 0.04, which were much lower than the corresponding 15.4, 187, and 0.06 for the

2 factories without RFs. PM EFs were not correlated with A_{ad} values in fuel coal and PM REs, which suggested the greater impact of combustion conditions and degree of incomplete coal combustion resulted therefrom. Also the lower mean value of SO_2 EF_I of 29 factories owning SO_2 RFs (REs from 10.0% to 89.3%) as 2.75 was obtained compared than 3.29 for the rest 8 ones without SO_2 RFs installed. An opposite tendency occurred at SO_2 EF_{II} and EF_{III} values due to the fluctuations of product prices and yields among different enterprises, high values (73.9 kg MY^{-1} and 0.02 kg t^{-1}) were attributed to enterprises owning RFs, while low values (57.6 kg MY^{-1} and 0.01 kg t^{-1}) were obtained for the factories without RFs. In regard to NO_x EFs, EF_I and EF_{III} value for 2 factories owning NO_x RFs (7.30 kg t^{-1} and 0.03 kg t^{-1}) were higher than those (5.26 kg t^{-1} and 0.03 kg t^{-1}) under the influence of nitrogen contents in coal, combustion temperature, and NO_x REs of RFs (Löffler et al., 2005; Li et al., 2018; Hu et al., 2019). Unlike SO_2 , NO_x mainly originated from oxidation of air N_2 at high temperature regardless of that small proportion of NO_x formed by burning of fuel-nitrogen, so NO_x emissions were more depended on the coal burning temperature and NO_x REs than SO_2 owing to the different formation mechanisms between them (Löffler et al., 2005).

A total of 23 small scale enterprises (SSEs) were involved in this study with their outputs ranged from 0.21

to 278 MY a⁻¹ and product yields varied from 2.80 to 372 kt a⁻¹. The weak correlation between output values and product yields ($R = 0.68$, $p < 0.05$) for SSEs compared with LSEs and MSEs were possibly attributed to the unstable sale prices resulted from the small enterprise size. Figs. 3 and 4 listed the EFs for each SSE and mean EF values for 23 SSEs. EF values defined as 3 expressions showed the same trends and followed the order as VOCs > NO_x > PM > SO₂, which were different from EFs of LSEs and MSEs. The increased PM EFs compared with MSEs and LSEs would be explained by back boilers applied in SSEs. The incomplete combustion of coal caused the enhanced carbon content (organic carbon and black carbon) in ash, further increased the mass of emitted PM. Meanwhile, the incomplete burning of coal also resulted in the increasing of VOCs emissions. The mean values of EFs for VOCs, PM, NO_x, and SO₂ from SSEs were EF_I (110, 6.41, 5.31, and 2.97 kg t⁻¹), EF_{II} (2280, 867, 370, and 262 kg MY⁻¹), and EF_{III} (0.50, 0.14, 0.07, and 0.04 kg t⁻¹), respectively (Fig. 4). 8, 21, and 5 of 23 SSEs were not equipped with SO₂, NO_x, and PM RFs. The relatively low SO₂ and NO_x EFs occurred at SSEs with corresponding RFs equipped, while PM showed the reverse trend. The mean SO₂ EF_I, EF_{II}, and EF_{III} values for 8 SSEs without RFs (3.45, 322, and 0.05) were much higher than the corresponding (2.71, 230, and 0.04) for 13 SSEs with RFs. The highest SO₂ EF_I

value of 7.52 kg t⁻¹ occurred at F59 without SO₂ RFs, while the lowest value of 0.95 kg t⁻¹ was possessed by F78 ascribe to its highest SO₂ RE of 89.3% among 23 SSEs. F67 possessed the highest EF_I and EF_{II} values of the sum of SO₂, PM, and NO_x, due to its low output and no installation of any RFs (Fig. 3). The maximum of NO_x EF_I, EF_{II}, and EF_{III} were all belong to F67, which could explained by its high nitrogen content, zero removal rate, and low output (Li et al., 2018; Hu et al., 2019). The mean NO_x EFs for SSEs owning RFs were 1.03 for EF_I, 52.4 for EF_{II}, and 0.01 for EF_{III}, which were significantly lower than the corresponding 6.92, 945, and 0.15 for the rest SSEs without NO_x RFs. PM EF_I values of SSEs with PM RFs equipped possessed slightly higher value (5.33) than the corresponding 5.25 for the rest SSEs without RFs, which was possibly resulted from ash content fluctuations and actual RFs running status.

Fig. 4 listed the mean values of EF_I, EF_{II}, and EF_{III} of 4 air pollutants for 19 LSEs, 37 MSEs, and 23 SSEs. Except for PM EFs, EFs for the other 3 air pollutants increased with the decreasing of scale of enterprises, especially for VOCs. The incomplete coal combustion of backward boilers applied in SSEs would be the explanation of increasing of VOCs EF_I values from 57.4 of LSEs to 110 of SSEs, EF_{II} values from 407 of LSEs to 2280 of SSEs, and EF_{III} values from 0.13 of LSEs to 0.50 of SSEs.

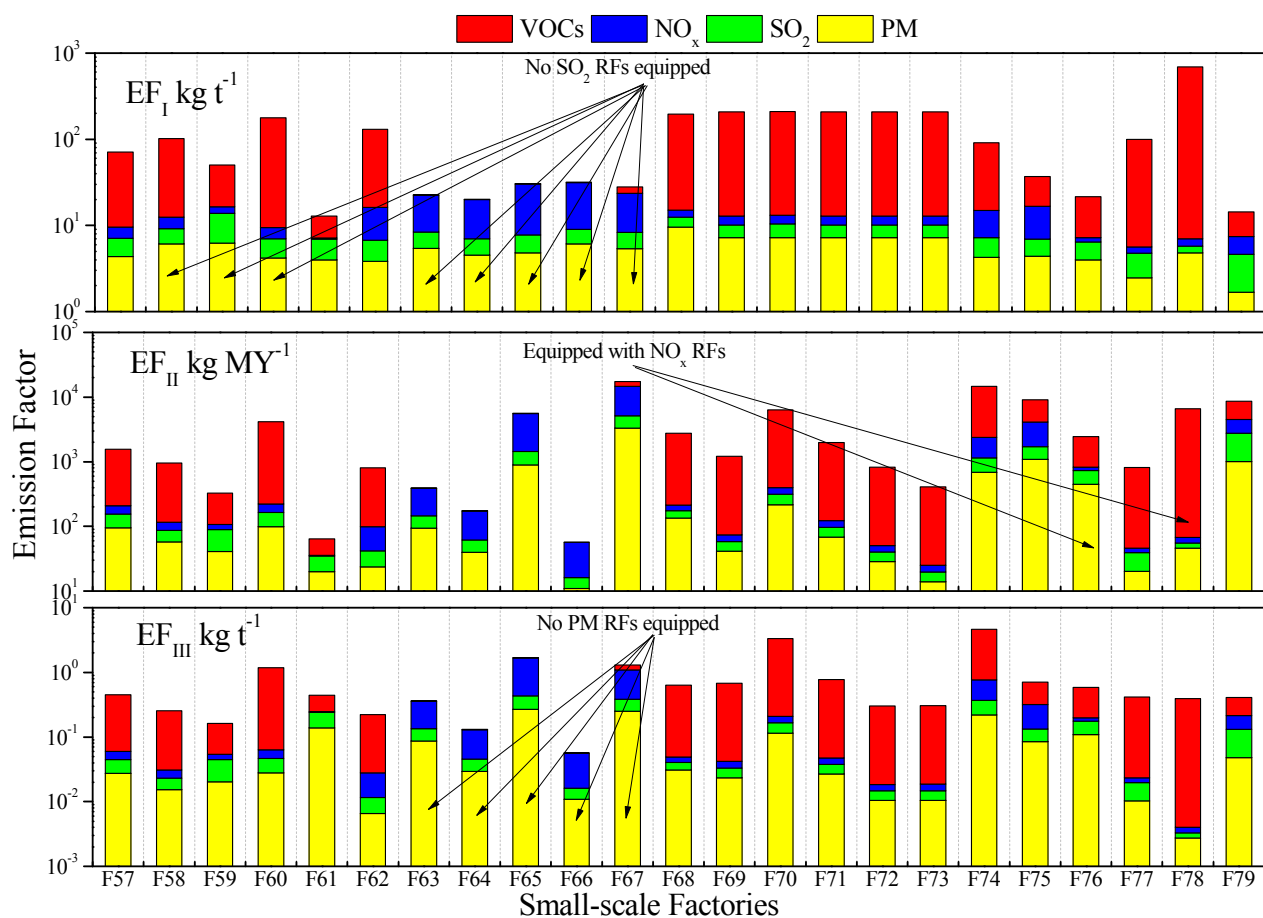


Fig. 3. Emission factors of the coal-fired boilers used in small-scale coal washing enterprises.

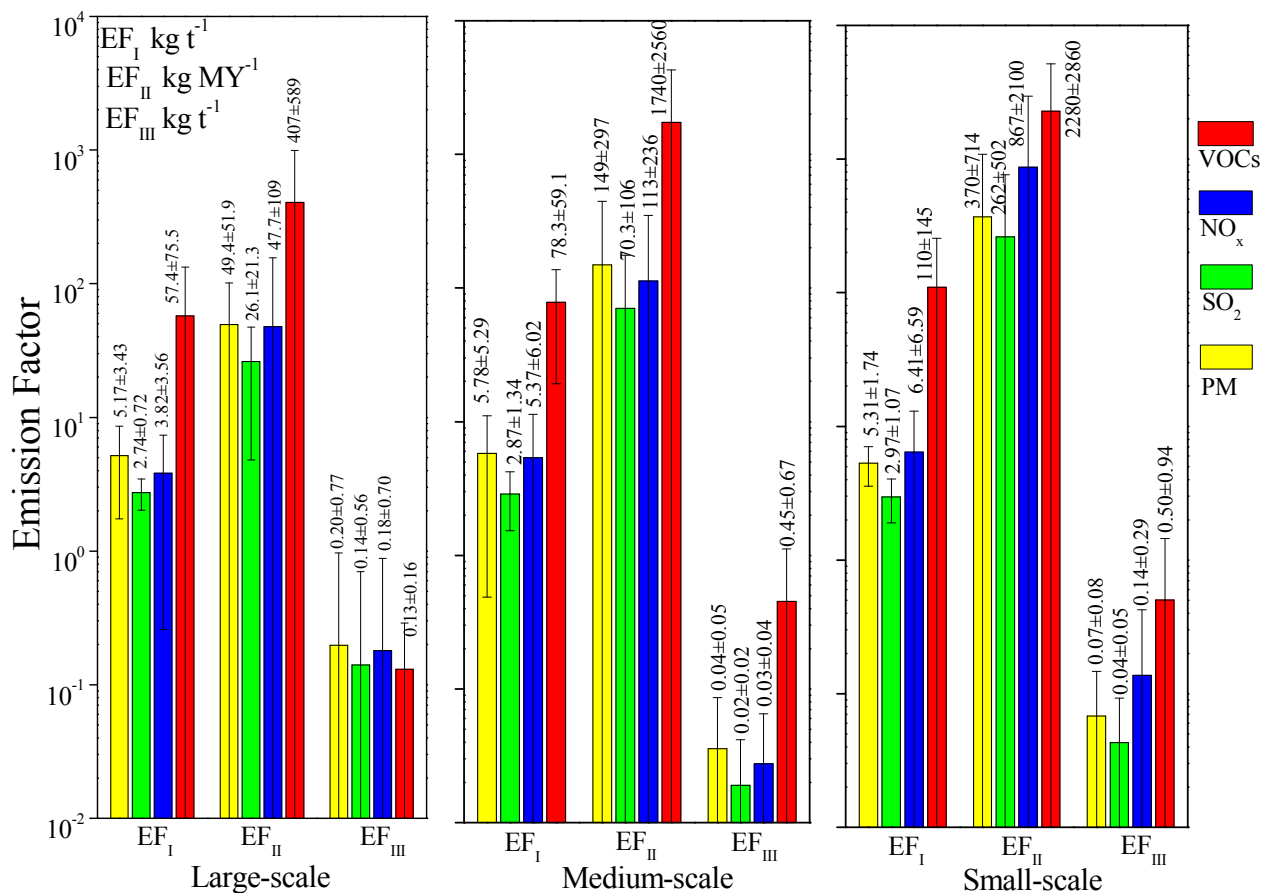


Fig. 4. Mean values of EFs of coal fired boilers for large-scale, medium-scale, and small-scale coal washing factories.

Emission Factors of Coal Fired Boilers in Iron-steel Manufacturing

Due to the limited experimental condition, VOCs field sampling was not conducted for coal-fired boilers applied in 8 iron-steel (IS) enterprises. All the 8 IS factories were equipped with PM RFs and not equipped with NO_x EFs, and SO₂ RFs were partly installed in 5 of 8 factories (Table 4). Figs. 5 and 6 listed the EFs for each IS factory and the mean values of EF_I, EF_{II}, and EF_{III} for 8 IS enterprises. The lowest pollutant EFs occurred at I7, EF_I values PM, NO_x, and SO₂ were 0.36, 0.07, and 0.74 kg t⁻¹, and the corresponding values were 165, 33.2, and 338 kg MY⁻¹ for EF_{II}, and 1.03, 0.21, and 2.10 kg t⁻¹ for EF_{III}, which might be explained by its lowest S_{ad} content, pollutant RFs, and actual combustion condition and running status of RFs (Fig. 5). The highest EF_I (73.0 kg t⁻¹) of the sum of PM, NO_x, and SO₂ occurred at I5, while the corresponding values for EF_{II} and EF_{III} were possessed by I4 (22900 kg MY⁻¹) and I3 (11.8 kg t⁻¹), respectively (Fig. 5).

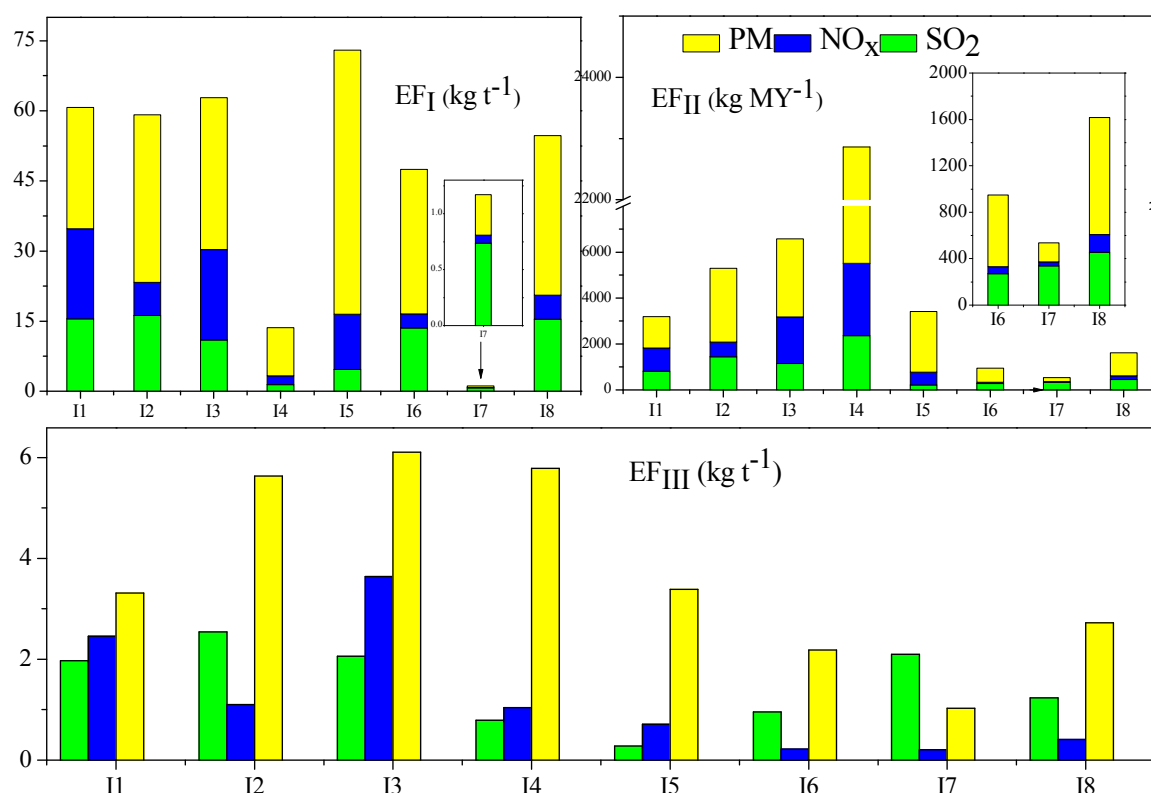
A lot of heat provided by coal- and coal-gas fired boilers was demanded for the production processes of iron and steel (Yan, 2012). Compared with the S_{ad} contents of fuel coal applied in CW LSEs (0.65%), MSEs (0.69%), and SSEs (0.80%), the lower mean value of 0.59% occurred at IS enterprises. Also lower mean value of A_{ad} of fuel coal for 8 IS enterprises (15.4%) was found compared with corresponding value of CW LSEs (17.5%), MSEs (15.8%),

and SSEs (16.4%). In regard to EF_I values (reported in kg t⁻¹) for 3 air pollutants, they followed the order as PM (28.3 ± 15.9) > SO₂ (9.80 ± 6.12) > NO_x (8.46 ± 7.10), which significantly differed from those of different scale coal washing enterprises, they were PM > NO_x > SO₂ for CW LSEs and MSEs, and NO_x > PM > SO₂ for CW SSEs. In regard to EF_I values (reported in kg t⁻¹), PM possessed much higher value of 28.3 than 5.17, 5.78, and 5.31 for CW LSEs, MSEs, and SSEs regardless of low ash contents of coal in IS industries and similar PM REs between CW and IS industries, which possibly resulted from the differences of production processes between two industries. The mean NO_x EF_I (reported in kg t⁻¹) for 8 IS enterprises (8.46) was also much higher than 3.82, 5.37, and 6.41 for CW LSEs, MSEs, and SSEs ascribe to no NO_x RFs installation in all the IS enterprise and combustion conditions. The SO₂ originated from IS enterprises also showed an enhanced average EF_I compared with those of 3 different scale CW enterprises.

The EF_{II} values of 3 air pollutants for 8 IS factories (reported in kg MY⁻¹) were 3720, 951, and 883 for the PM, NO_x, and SO₂, respectively. The different sort order between EF_I and EF_{II} for 8 IS enterprises was mainly attributed to the fluctuation of output. The EF_{III} values (reported in kg t⁻¹) for 8 IS factories followed the same order with EF_I, they were PM (3.77 ± 1.75) > SO₂ (1.49 ± 0.74) > NO_x (1.22 ± 1.14). Due to the differences existed in product prices,

Table 4. Statistical values for 8 iron-steel production enterprises.

	S _{ad} (%)	A _{ad} (%)	CC (kt a ⁻¹)	PM RE (%)	SO ₂ RE (%)	NO _x RE (%)	Product	Output (MY a ⁻¹)	Product (kt a ⁻¹)
I1	0.33	13.0	291	98.3	61.6	0.00	Steel	5550	2290
I2	0.4	12.0	49.6	96.5	30.3	0.00	Iron	555	316
I3	0.37	13.0	29.8	99.0	41.5	0.00	Iron	284	158
I4	1.00	11.5	303	98	89.4	0.00	Steel	180	540
I5	0.75	11.0	38.6	97.2	78.9	0.00	Sinter	824	644
I6	0.60	27.0	0.34	95.0	0.00	0.00	Reduced iron	17.0	4.80
I7	0.30	15.0	8.55	96.5	0.00	0.00	Reduced iron	19.0	3.00
I8	0.97	21.0	0.07	70.0	0.00	0.00	corundum	2.30	0.85

**Fig. 5.** Emission factors of the coal fired boilers for each iron-steel production enterprise.

product yields, and output values between CW and IS industries, EF_{II} and EF_{III} values for IS were much higher than the corresponding values for CW.

The SO₂ originated from 5 enterprises with SO₂ RFs installed possessed lower mean EF_I of 9.74 than 9.90 of the rest 3 ones without SO₂ RFs, while higher EF_{II} and EF_{III} values occurred at 5 factories owning RFs compared with those of the rest 3 factories without RFs resulted from the fluctuations of outputs and product yields.

Emission Factors of Coal-fired Boilers in Lime and Gypsum Making Factories

As shown in Table 5, all the 4 LG factories equipped with PM and SO₂ RFs, and only 1 factory equipped with NO_x RFs, while no factories were installed with VOCs RFs. The output values ranged from 0.50 to 44.8 MY a⁻¹

with the mean value as 22.2 ± 22.9 MY a⁻¹, which were much lower than those of CW and IS industries. The sulfur contents and ash contents for 4 LG factories were much lower than those of CW and LG enterprises. The highest SO₂, VOCs, and NO_x EF_I values occurred at L3, they were 7.73, 11.5, and 10.2 kg t⁻¹, while the corresponding lowest values were possessed by L2 (1.54 kg t⁻¹), L4 (0.18 kg t⁻¹), and L1 (1.40 kg t⁻¹), respectively.

Fig. 7 list the EF_I, EF_{II}, and EF_{III} values of 4 air pollutants for coal fired boilers applied in 4 LG enterprises. The highest EF_I values (reported in kg t⁻¹) of SO₂ (7.73), NO_x (10.2), and VOCs (11.5) occurred at L3, while the correspondingly lowest values were attributed to L1 (1.37), L1 (1.40), and L4 (0.18), respectively. In regard to PM, EF_I maximum was possessed by L1 (8.41), while the lowest one occurred at L4 (1.37) (Fig. 7). The weak correlation

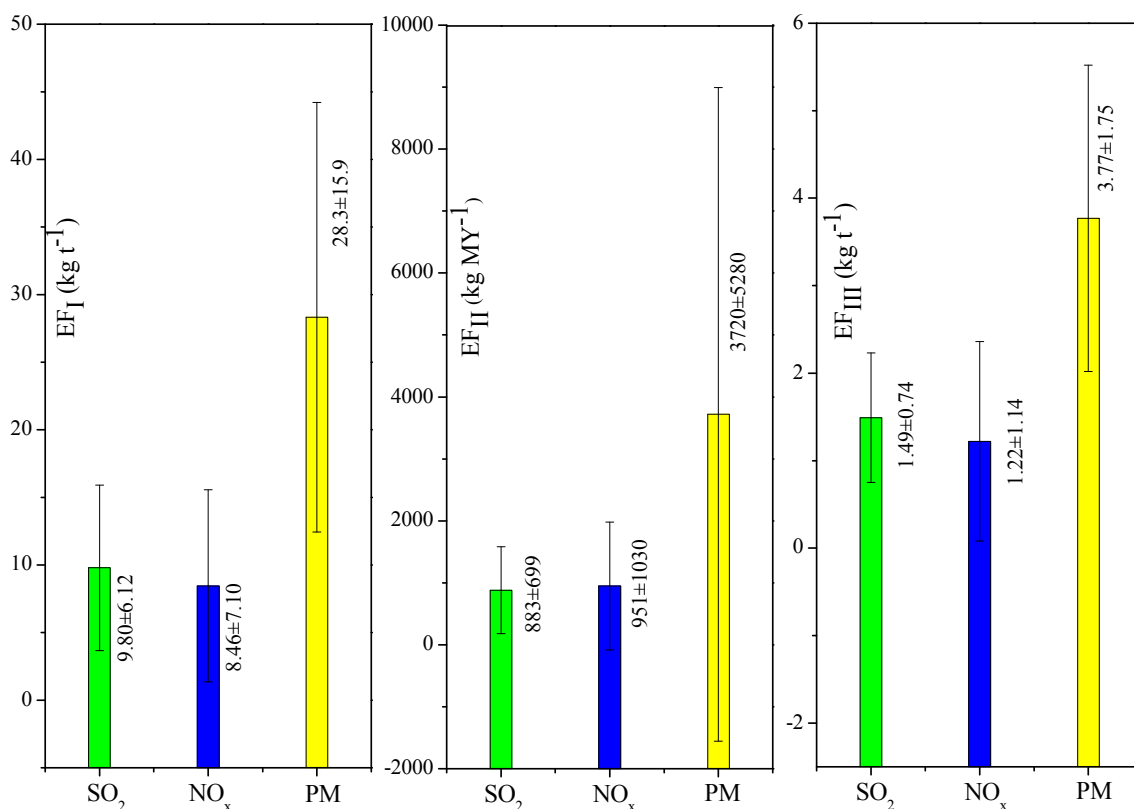


Fig. 6. Mean values of EFs for 3 air pollutants from coal fired boilers for 8 iron-steel production enterprises.

Table 5. Statistical values for 4 lime and gypsum production enterprises.

	S _{ad} (%)	A _{ad} (%)	CC (kt a ⁻¹)	RE (%)				Product	Output (MY a ⁻¹)	Yield (kt a ⁻¹)
				PM	SO ₂	NO _x	VOCs			
L1	0.30	7.00	27.0	99.0	10.1	8.17	0.00	Lime	44.8	160
L2	0.60	9.00	0.90	95.0	10.1	0.00	0.00	Light burnt dolomite	0.50	6.00
L3	0.40	17.0	2.60	99.0	25.3	0.00	0.00	Quick lime	39.0	160
L4	0.10	17.0	5.40	98.0	81.7	0.00	0.00	Lime	4.50	50.0

between EFs of air pollutants and corresponding RFs indicated the impact of actual running status of RFs and combustion of boilers.

The mean values of EF_I for 4 air pollutants followed the order as PM (5.10 ± 2.57) > NO_x (3.93 ± 3.66) > VOCs (3.49 ± 4.66) > SO₂ (3.21 ± 2.63), significantly differed from the orders PM > SO₂ > NO_x for IS industries, VOCs > PM > NO_x > SO₂ for CW LSEs, VOCs > PM > NO_x > SO₂ for CW MSEs, and VOCs > NO_x > PM > SO₂ for CW SSEs, which suggested the influence of comprehensive factors including coal compositions, production processes, combustion conditions, and pollutant removal technologies and removal efficiencies. VOCs EF_I for LG enterprises were far less than those of CW factories, indicated the impact of combustion completeness and production procedures. PM EF_I values of LG enterprises were compared to those of CW factories with different scale, but much lower than those of IS industry. Mean NO_x EF_I of LG plants was higher than that of CW LSEs, but much lower than that of CW MSEs, CW SSEs, and IS factories. In regard to SO₂,

they followed the order as IS > LG > CW.

Both EF_{II} and EF_{III} values for LG enterprises were subordinated to the order PM > NO_x > SO₂ > VOCs, which was different from EF_I due to the impact of output and product yield.

CONCLUSIONS

79 coal washing (CW) enterprises (19 large-, 37 medium-, and 23 small-scale factories), 8 iron-steel (IS) factories, and 4 lime and gypsum (LG) plants within Shanxi Province were investigated, sampled, and subsequently detected to obtain the coal consumption, output, and product yield associated emission factors for VOCs, NO_x, SO₂, and PM.

EF_I values of SO₂, NO_x, and VOCs increased with decreasing of scale of CW enterprises, while medium scale coal washing enterprises possessed the highest PM EF_I values. EF_I of SO₂ increased from 2.74 of LSEs to 2.97 kg t⁻¹ of SSEs, and they were from 3.82 of LSEs to 6.41 kg t⁻¹ of SSEs for NO_x, and from 57.4 of LSEs to 110 kg t⁻¹ of

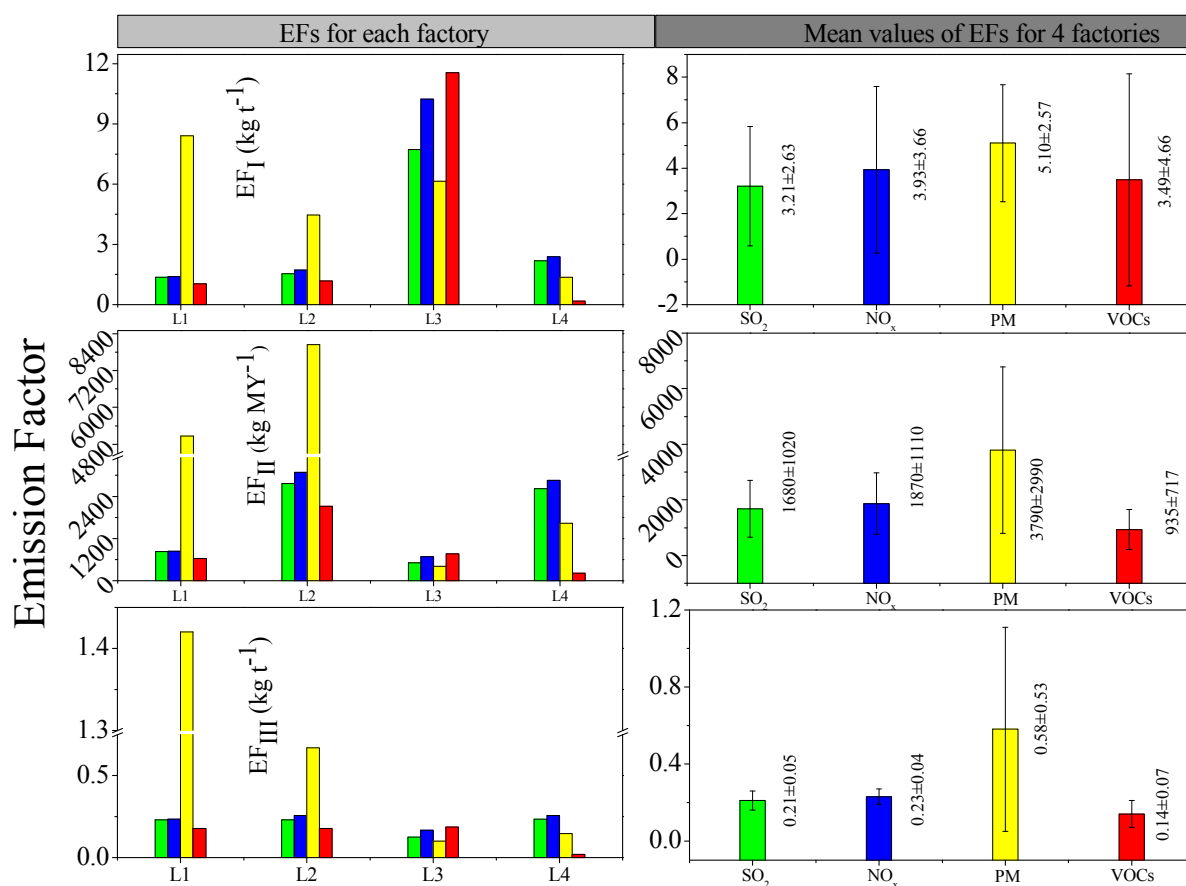


Fig. 7. Emission factors of the coal fired boilers used in lime and gypsum making enterprises.

SSEs for VOCs, respectively. Considering PM EF_I values (reported in kg t⁻¹), the MSEs possessed higher value of 5.78 than 5.17 for LSEs and 5.31 for SSEs, which might be explained by the actual running status of RFs and ash content contained in fuel coal. EF_{II} values (reported in kg MY⁻¹) for all the 4 air pollutants also increased with the decreasing of enterprise scales, which increased from 49.4 of LSEs to 370 of SSEs for PM, from 26.1 of LSEs to 262 of SSEs for SO₂, from 47.7 of LSEs to 867 of SSEs for NO_x, and from 407 of LSEs to 2280 of SSEs for VOCs, respectively. However, EF_{III} values showed different trends compared with EF_I and EF_{II} values for 4 air pollutants except for VOCs.

The weak correlation of EFs air pollutants vs. designed REs of RFs, and EFs vs. coal components was found among three types of industries indicated the great impact of actual running status of RFs and burning condition. IS industry possessed much higher EF_I values of PM, NO_x, and SO₂ than those of CW- and LG- industries. The mean values of EF_I (reported in kg t⁻¹) for 4 air pollutants for LG enterprises followed the order as PM (5.10 ± 2.57) > NO_x (3.93 ± 3.66) > VOCs (3.49 ± 4.66) > SO₂ (3.21 ± 2.63), significantly differed from the orders PM (28.3 ± 17.0) > SO₂ (9.80 ± 6.54) > NO_x (8.46 ± 7.60) for IS industries, VOCs (57.4 ± 75.5) > PM (5.17 ± 3.43) > NO_x (3.82 ± 3.56) > SO₂ (2.74 ± 0.72) for CW LSEs, VOCs (78.3 ± 75.5) > PM (5.78 ± 5.29) > NO_x (5.37 ± 6.02) > SO₂ (2.87

± 1.34) for CW MSEs, and VOCs (110 ± 145) > NO_x (6.41 ± 6.59) > PM (5.31 ± 1.74) > SO₂ (2.97 ± 1.07) for CW SSEs, which suggested the influence of comprehensive factors including coal compositions, production processes, combustion conditions, and pollutant removal technologies and removal efficiencies. For EF_{II} values of SO₂, NO_x, and PM, LG dominated in 3 industries, while the corresponding maximum of VOCs occurred at CW industry. Higher mean EF_{II} value (reported in kg MY⁻¹) for SO₂ (1680), NO_x (1870), and PM (3790) were owned by LG compared with 883, 951, and 3720 for IS, 26.1, 47.7, and 49.4 for CW LSEs, 70.3, 113, and 149 for CW MSEs, and 262, 867, and 370 for CW SSEs, respectively. In regard to SO₂, NO_x, and PM EF_{III} values (reported in kg t⁻¹), higher values of 1.49, 1.22, and 3.77 occurred at IS, and the correspondingly lower values were 0.21, 0.23, and 0.58 for LG, 0.14, 0.18, and 0.20 for CW LSEs, 0.02, 0.03, and 0.04 for CW MSEs, and 0.04, 0.07, and 0.14 for CW SSEs, respectively.

In a word, EFs should be designated for the specific industry and the industry scale. The pollutant removal facilities must be improved, especially for VOCs removal equipments in CW industry. SO₂ RFs have been installed for most of enterprises of three types of industries, and the SO₂ RFs should be installed for the remaining small part of enterprises. The low cost NO_x removal measures such as fuel and air classification combustion, injection of ammonia and urea into furnace, changing of burning temperature

should be adopted as soon as possible for the most of enterprises within these 3 industries. The PM RFs were equipped for almost all the enterprises and the running status and time should be optimized to obtain the enhanced PM removal efficiencies.

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SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at <http://www.aaqr.org>.

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