Emissions of NOx, 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) were lack in present China. CFBs of 91 enterprises involving CW, IS, and LG were to obtain their pollutant EFs associated with coal consumptions (EFI, kg t\(^{-1}\)), outputs (EFII, kg MY\(^{-1}\)), and product yields (EFIII, 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 running status of RFs. EFs of VOCs from small-scale CW enterprises (SSEs) were much higher than those of large- and medium-scale enterprises (LSEs and MSEs) owning to the incomplete combustion of coal. Also the SO2 and NOx EFs of CW increased with decreasing enterprise scale, while the PM maximum occurred at MSEs. The mean EFI values of LG for 4 air pollutants followed the order as PM> NOx> VOCs> SO2, differed from PM> SO2> NOx for IS, VOCs> PM> NOx> SO2 for CW LSEs and MSEs, and VOCs> NOx> 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. EFl values for 8 IS factories were subordinated to the order PM> SO2> NOx, while they were PM> NOx> SO2 for EFII values due to their output fluctuation. For EFII and EFIII values of SO2, NOx, and PM, LG dominated within 3 industries, while the corresponding maximum of VOCs occurred at CW industry.

Keywords: Emission Factor; Coal Washing; Lime-Gypsum Making; SO2; NOx; VOCs

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INTRODUCTION

With rapid economic development and urbanization, air pollution has become an increasingly serious issue in China, the severe regional air pollution were 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, NOx, 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 pollutants (SO2, NOx, 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 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 pollutant, 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 (SO4\(^{2-}\), 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; Jayaratne 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 SO4\(^{2-}\) etc., and the main forms lie in combustion residues are FeS\(_2\), CaSO\(_4\), FeSO\(_4\), 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, NOx, CH\(_4\), VOCs, and inorganic acid (Stockwell et al., 2015, 2016; Goetz et al., 2018).
Shanxi and Inner Mongolia are two predominant coal districts in China, whose coal production accounted for 49.2% and 51% of Chinese total output in 2016 and 2017, respectively. The coal goaf area of Shanxi is as high as 20,000 km², accounted almost 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 process, and flotation separation and so on for the reduction of noncombustible minerals, acid precursor 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 $1\times10^8$ t coal can reduce the emission of $6-7\times10^5$ t SO₂, and $1.61\times10^7$ 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, NOₓ, 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, and field sampled 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, NOx, 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 NOx were real-time monitored using a flue gas analyzer, while VOCs in flue gas were sampled and subsequently analyzed by a GC-MS system.

Table 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 Table 4 and Table 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 VOCs removal facilities (RFs). NOx RFs were installed in a small number of factories, while PM RFs were installed in all the 91 factories.

Sampling and Measurement of SO2, NOx, and PM

The same method for sampling and measurement of SO2, NOx (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, NOx, 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\(_x\), SO\(_2\) and O\(_2\)) before measurement for the elimination of possible interferences. The mass emissions of SO\(_2\), 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 procedure of VOCs was divided to 3 successive steps including 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 1S.

**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).

\[
\text{EF}_I (\text{kg t}^{-1}) = \frac{C (\text{kg m}^{-3}) \times V_{FA} (\text{m}^3 \text{kg}^{-1}) \times 1000 \text{ kg t}^{-1}}{}
\] (1)
Where \( C \) is mass concentrations of gaseous pollutants, \( V_{FA} \) is the actual flue gas volume derives from 1 kg coal burning, which can be induced by \( V_{AT} \).

\[
EF_{H}(\text{kg MY}^{-1}) = \frac{C (\text{kg m}^{-2}) \times (1000 \text{ kg t}^{-1}) \times V_{FA}(\text{m}^3 \text{ kg}^{-1}) \times \text{Coal consumption (t a}^{-1}) \times \text{Output (MY a}^{-1})}{\text{Product yield (t a}^{-1})}
\]

\[
EF_{H}(\text{kg t}^{-1}) = \frac{C (\text{kg m}^{-2}) \times (1000 \text{ kg t}^{-1}) \times V_{FA}(\text{m}^3 \text{ kg}^{-1}) \times \text{Coal consumption (t a}^{-1})}{\text{Product yield (t a}^{-1})}
\]

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

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

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

\[
V_{FT} = V_{CO2} + V_{SO2} + V_{NO2} + V_{N2} + V_{H2O}
\]

\[
V_{CO2} + V_{SO2} + V_{NO2} = 0.01867 \omega(C_{ar}) + 0.007 \omega(S_{ar}) + 0.0016 \omega(N_{ar})
\]

Where \( V_{CO2}, V_{SO2}, \text{ and } V_{NO2} \) refer to volumes of CO\(_2\), SO\(_2\), and NO\(_2\) derived from burning of C, H, and N in coal, \( V_{N2} \) is the N\(_2\) volume in \( V_{AT} \) and equal to 0.79\( V_{AT} \), and \( V_{H2O} \) 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 (0.0161\( V_{AT} \)).

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

\[
V_{FA} = V_{FT} + (\alpha - 1)V_{AT} + 0.0161(\alpha - 1)V_{AT}
\]

Where \( \alpha \) is the excess air coefficient, which is provided by corresponding enterprise.

**RESULTS AND DISCUSSION**

**Emission Factors of NO\(_x\), VOCs, SO\(_x\), 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 Table 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 ($R^2=0.66$, $p<0.05$).

(Table 1)

Among 79 coal washing enterprises, only 8 ones were not installed with PM RFs, 18 ones were not equipped with SO$_2$ 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±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. SO$_2$ 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, NH$_3$·H$_2$O 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.

(Table 3)

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

(Fig. 1)
Fig. 1 and Fig. 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 > NO\textsubscript{x} > SO\textsubscript{2}. For EF_{I} values (in kg t\textsuperscript{-1}), 0.06–180 (57.4±75.5), 0.99–12.8 (5.17±3.43), 0.44–15.8 (3.82±3.56), and 1.06–4.18 (2.74±0.721) were attributed to VOCs, PM, NO\textsubscript{x}, and SO\textsubscript{2}, respectively. Compared with other 3 air pollutants, SO\textsubscript{2} EF values possessed smaller fluctuation, while Hu et al. (2019) reported that NO\textsubscript{x} has smaller fluctuation, which could be explained by the fluctuation of RFs. The mean value of SO\textsubscript{2} EF\textsubscript{I} of F6, and F19 without SO\textsubscript{2} RFs equipped was 2.80 kg t\textsuperscript{-1}, which was higher than the mean value of 2.73 kg t\textsuperscript{-1} for the rest 17 enterprises. The highest SO\textsubscript{2} EF\textsubscript{I} occurred at F11 (4.18 kg t\textsuperscript{-1}), while the lowest value of 1.06 kg t\textsuperscript{-1} occurred at F5. EF\textsubscript{I} values of 19 enterprises were better correlated with SO\textsubscript{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\textsubscript{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\textsubscript{x} EF\textsubscript{I}, 6 LSEs with RFs installed including F3, F10, F11, F12, F13, and F14 possessed the lower mean value of 3.52 kg t\textsuperscript{-1} than that (3.96 kg t\textsuperscript{-1}) of the rest 13 enterprises, suggested the impact of NO\textsubscript{x} RFs. Only F6 was not equipped PM RFs, it had higher PM EF\textsubscript{I} value of 7.21 kg t\textsuperscript{-1} than the mean value of 5.06 kg t\textsuperscript{-1} for the rest 18 enterprises without PM RFs. VOCs possessed the highest EF\textsubscript{I} reflected the no VOCs RFs were installed in all the 19 LSEs.

Due to the well correlation between outputs and coal consumptions, EF\textsubscript{II} values (in kg MY\textsuperscript{-1}) for these 79 enterprises exhibited the similar order as VOCs (407±589)> PM (49.4±53.4)> NO\textsubscript{x} (47.7±109)> SO\textsubscript{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\textsubscript{I} and EF\textsubscript{II} values showed the similar fluctuation. The EF\textsubscript{II} values (in kg MY\textsuperscript{-1}) for PM, SO\textsubscript{2}, and NO\textsubscript{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\textsubscript{2} EF\textsubscript{II} values showed a better correlation with SO\textsubscript{2} REs (R= –0.45) than S_{ad} values of fuel coals (R= –0.09), which was similar to EF\textsubscript{I} values.

Due to the differences of coal washing processes and product yields, EF\textsubscript{III} values (in kg t\textsuperscript{-1}) of 4 air pollutants for 19 LSEs differentiated from their EF\textsubscript{I} and EF\textsubscript{II} values, they complied with the order of PM (0.20±0.77) > NO\textsubscript{x} (0.18±0.70) > SO\textsubscript{2} (0.14±0.56) > VOCs (0.13±0.16).

(Fig. 2)

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\textsubscript{x} RFs with REs as 59.5% and 15.0%, 8 MSEs were not equipped with SO\textsubscript{2} RFs, and all the
37 MSEs were not installed with VOCs RFs and were equipped with PM RFs. Fig. 2 and Fig. 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\textsubscript{X} (5.37±6.02)> SO\textsubscript{2} (2.87±1.34) for EF_I (in kg t\textsuperscript{-1}), VOCs (1740±2560)> PM (149±297)> NO\textsubscript{X} (113±236)> SO\textsubscript{2} (70.3±106) for EF_{II} (in kg MY\textsuperscript{-1}), while they were VOCs (0.45±0.67)> PM (0.04±0.05)> NO\textsubscript{X} (0.03±0.04)> SO\textsubscript{2} (0.02±0.02) for EF_{III} (in kg t\textsuperscript{-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\textsuperscript{-1} of F43 to 252 kg t\textsuperscript{-1} of F39, 3.9 kg MY\textsuperscript{-1} of F56 to 14300 kg MY\textsuperscript{-1} of F51, and 1.00×10\textsuperscript{-3} kg t\textsuperscript{-1} of F56 to 1.56 kg t\textsuperscript{-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\textsubscript{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\textsubscript{2} EF of 29 factories owning SO\textsubscript{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\textsubscript{2} RFs installed. An opposite tendency occurred at SO\textsubscript{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\textsuperscript{-1} and 0.02 kg t\textsuperscript{-1}) were attributed to enterprises owning RFs, while low values (57.6 kg MY\textsuperscript{-1} and 0.01 kg t\textsuperscript{-1}) were obtained for the factories without RFs. In regard to NO\textsubscript{X} EFs, EF_I and EF_{III} value for 2 factories owning NO\textsubscript{X} RFs (7.30 kg t\textsuperscript{-1} and 0.03 kg t\textsuperscript{-1}) were higher than those (5.26 kg t\textsuperscript{-1} and 0.03 kg t\textsuperscript{-1}) under the influence of nitrogen contents in coal, combustion temperature, and NO\textsubscript{X} REs of RFs (Löffler et al., 2005; Li et al., 2018; Hu et al., 2019). Unlike SO\textsubscript{2}, NO\textsubscript{X} mainly originated from oxidation of air N\textsubscript{2} at high temperature regardless of that small proportion of NO\textsubscript{X} formed by burning of fuel-nitrogen, so NO\textsubscript{X} emissions were more depended on the coal burning temperature and NO\textsubscript{X} RFs than SO\textsubscript{2} owning to the different formation mechanisms between them (Löffler et al., 2005).

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Fig. 3)

A total of 23 small scale enterprises (SSEs) were involved in this study with their outputs ranged from 0.21 to 278 MY a\textsuperscript{-1} and product yields varied from 2.80 to 372 kt a\textsuperscript{-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. Fig. 3 and Fig. 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 > NOx > 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, NOx, 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, NOx, and PM RFs. The relatively low SO2 and NOx 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 NOx, due to its low output and no installation of any RFs (Fig. 3). The maximum of NOx 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 NOx 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 NOx 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)

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.

Emission Factors of Coal Fired Boilers in Iron-Steel Manufacturing

(Table 4)

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 NOx EFs, and SO2 RFs were partly installed in 5 of 8 factories (Table 4). Fig. 5 and Fig. 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, NOx, 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, NOx, 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).

(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)> NOx (8.46±7.10), which significantly differed from those of different scale coal washing enterprises, they were PM> NOx> SO2 for CW LSEs and MSEs, and NOx> PM> SO2 for CW SSEs. In regard 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 NOx 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 NOx 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, NOx, 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)> NOx (1.22±1.14). Due to the differences existed in product prices, 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.

(Fig. 6)

**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 SO$_2$ 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 SO$_2$, 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. 

(Table 5)

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 SO$_2$ (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 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)> SO$_2$ (3.21±2.63), significantly differed from the orders PM > SO$_2$ > NO$_x$ for IS industries, VOCs > PM > NO$_x$ > SO$_2$ for CW LSEs, VOCs > PM > NO$_x$ > SO$_2$ for CW MSEs, and VOCs > NO$_x$ > PM > SO$_2$ 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 SO$_2$, 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$_x$ > SO$_2$ > 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, NOₓ, SO₂, and PM.

EF₁ values of SO₂, NOₓ, and VOCs increased with decreasing of scale of CW enterprises, while medium scale coal washing enterprises possessed the highest PM EF₁ values. EF₁ 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 NOₓ, and from 57.4 of LSEs to 110 kg t⁻¹ of SSEs for VOCs, respectively. Considering PM EF₁ 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. EF₁ 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 NOₓ, and from 407 of LSEs to 2280 of SSEs for VOCs, respectively. However, EF₁values showed different trends compared with EF₁ and EF₁ 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 EF₁ values of PM, NOₓ, and SO₂ than those of CW- and LG- industries. The mean values of EF₁ (reported in kg t⁻¹) for 4 air pollutants for LG enterprises followed the order as PM (5.10±2.57)> NOₓ (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)> NOₓ (8.46±7.60) for IS industries, VOCs (57.4±75.5)> PM (5.17±3.43)> NOₓ (3.82±3.56)> SO₂ (2.74±0.72) for CW LSEs, VOCs (78.3±75.5)> PM (5.78±5.29)> NOₓ (5.37±6.02)> SO₂ (2.87±1.34) for CW MSEs, and VOCs (110±145)> NOₓ (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 EF₁ values of SO₂, NOₓ, and PM, LG dominated in 3 industries, while the corresponding maximum of VOCs occurred at CW industry. Higher mean EF₁ value (reported in kg MY⁻¹) for SO₂ (1680), NOₓ (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, NOₓ, and PM EF₁ 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 NOx 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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Table Captions

Table 1. Statistical values for large scale coal washing enterprises
Table 2. Statistical values for medium scale coal washing enterprises
Table 3. Statistical values for small scale coal washing enterprises
Table 4. Statistical values for 8 iron-steel production enterprises
Table 5. Statistical values for 4 lime and gypsum production enterprises
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       |
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       |
Table 3 Statistical values for small 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(%) |
|-------|-------------|-----------|------------|------------|---------|------------|--------------|--------------|----------|-----------|
| F57   | 55.0        | 1.20      | 0.35       | 16.0       | raw coal| 190        | 27.2         | 0.00         | 98.9     | 0.00      |
| F58   | 80.0        | 0.75      | 0.50       | 17.0       | raw coal| 300        | 0.00         | 0.00         | 98.8     | 0.00      |
| F59   | 105.0       | 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       | 0.73      | 0.30       | 14.7       | raw coal| 21.0       | 22.1         | 0.00         | 99.0     | 0.00      |
| F62   | 195.0       | 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       | 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       | 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   | 189.0       | 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      |
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\(^{-1}\)) |
|----------|----------|----------------------|------------|----------------|----------------|-------------------|-------------------------|--------------------------|
| 11 0.33  | 13.0     | 291                  | 98.3       | 61.6           | 0.00           | Steel             | 5550                    | 2290                     |
| 12 0.4   | 12.0     | 49.6                 | 96.5       | 30.3           | 0.00           | Iron              | 555                     | 316                      |
| 13 0.37  | 13.0     | 29.8                 | 99.0       | 41.5           | 0.00           | Iron              | 284                     | 158                      |
| 14 1.00  | 11.5     | 303                  | 98         | 89.4           | 0.00           | Steel             | 180                     | 540                      |
| 15 0.75  | 11.0     | 38.6                 | 97.2       | 78.9           | 0.00           | Sinter            | 824                     | 644                      |
| 16 0.60  | 27.0     | 0.34                 | 95.0       | 0.00           | 0.00           | Reduced iron      | 17.0                    | 4.80                     |
| 17 0.30  | 15.0     | 8.55                 | 96.5       | 0.00           | 0.00           | Reduced iron      | 19.0                    | 3.00                     |
| 18 0.97  | 21.0     | 0.07                 | 70.0       | 0.00           | 0.00           | corundum          | 2.30                    | 0.85                     |
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\(^{-1}\)) |
|-------------|------------|----------------------|--------|---------|-------------------------|------------------------|
| 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 |
Figure Captions

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

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

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

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

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

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

Fig. 7. Emission factors of the coal fired boilers used in lime and gypsum making enterprises
Fig. 1. Emission factors of the coal-fired boilers used in large-scale coal washing enterprises
Fig. 2. Emission factors of the coal-fired boilers used in medium-scale coal washing enterprises.
No SO2 RFs equipped

Equipped with NOx RFs

No PM RFs equipped

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.
Fig. 5. Emission factors of the coal fired boilers for each iron-steel production enterprise
Fig. 6. Mean values of EFs for 3 air pollutants from coal fired boilers for 8 iron-steel production enterprises
Fig. 7. Emission factors of the coal fired boilers used in lime and gypsum making enterprises