Emission Factors of NO_x, SO_2, and PM for Bathing, Heating, Power Generation, Coking, and Cement Industries in Shanxi, China: Based on Field Measurement

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ABSTRACT

Despite the rapid development of China's industries, the small-scaled boilers (SCBs) still occupy a large proportion. The huge pollutant emissions of SCBs should be paid more attention due to the lack of pollutant removal devices (RDs). In this study, various SCBs (the involved fuels include coal, gangue, coke oven gas, coal gas, and natural gas) applied in bathing, heating, power generation, and coke and cement making were investigated for SO_2, NO_x, and PM emission factors (EFs). EFs were expressed by pollutant mass per fuel consumption as EF_I, per product yield as EF_{II}, per industrial output as EF_{III}, and per power generation as EF_{IV}. Among 17 civil SCBs, 4, 14, and 10 ones were not equipped with PM, NO_x, and SO_2 RDs, respectively. Generally the EF_I values for 17 civil SCBs decreased with the increase of their coal consumptions. The average of NO_x EF_I values for 3 SCBs with NO_x RDs installed was 2.00 kg t^{-1}, while it was 3.16 kg t^{-1} for 17 SCBs. The sulfur content of coal and SO_2 removal rate were important influencing factors on the SO_2 EF_I values. The 4 companies without PM RDs possessed the average of EF_I values as 23.9kg t^{-1}, higher than the corresponding 5.41 kg t^{-1} for 13 ones equipped with PM RDs. EF_I, EF_{II}, and EF_{IV} for 9 coal-fired power plants (PPs) showed the same trends, the EF values for coal-fired PPs decreased from 6MW to 330 or 300 MW, while the 600 MW possessed slightly higher EFs than 330 MW. Gas-fired PPs possessed higher NO_x EFs than coal- and gangue-fired ones. Gangue-fired PPs possessed significantly higher EFs than coal-fired PPs with the same individual block power capacity. Because the flue gas for coking industry was not fully emitted from combustion process, there was no correlation between the EFs (expressed as EF_{II} and EF_{III}) and their coke productions or industrial outputs. The NO_x EFs for coking were higher than SO_2 and PM due to the lack of NO_x RDs. For 6 small- and medium-sized cement companies, higher PM EF_I occurred at the company with lower cement production. A reverse trend possessed by NO_x EF_I, high combustion temperature of company with high cement production was the possible explanation.

Keywords: Emission factor; SO_2; NO_x; Bathing; Coke making; Power plant; Cement making

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INTRODUCTION

Atmospheric quality deterioration has occurred in Asian, European and North American cities in recent years, and especially in some rapidly developing regions and countries (e.g. China) (Fang *et al.*, 2009; Pascal *et al.*, 2013; Kiros *et al.*, 2016; Li *et al.*, 2017). The focus on Chinese pollutant emissions is still rising because various emission sources, emission intensities, and spatial and temporal emission patterns are contained in this country (Zhao *et al.*, 2017).

Emission inventory is a key factor to the atmospheric science research and policy making on pollution control. The accuracy of emission inventory depends largely on accurate EFs. Although a series of pollution control measures have been conducted to improve air quality and protect human health in China, SO_2, NO_x, and PM are still the primary air pollutants (Zhong *et al.*, 2017). SO_2 has a harmful effect to human health, leads to acid rain and the increase of PM (Annamalai *et al.*, 2016). NO_x (NO or NO_2) plays a key role in atmospheric chemistry, it can cause depletion of stratospheric O_3, formation of acid rain and organic aerosols, and results in seriously adverse health effects such as respiratory effects, cardiovascular effects, lung cancer, and mortality (Yao *et al.*, 2015; Xu *et al.*, 2017a; Yan *et al.*, 2017; Wang *et al.*, 2018). PM especially fine PM as $PM_{2.5}$ and PM_{10}, not only poses a serious threat to human health but also scatters and adsorbs the incident light, and results in atmospheric opacity and horizontal visibility reduction (Mari *et al.*, 2016; Ma *et al.*, 2017a).

SO_2, NO_x, and PM are always formed and emitted from fossil and biomass burning process (Liu *et al.*, 2017). Industrial boilers for production of the glass, paper, plastic, cement, and chemicals are the main sources of industrial SO_2, NO_x, and PM (Zhang *et al.*, 2015; Wang and Chen, 2016). Compared with industrial boilers, an unknown number of civil boilers have been the other important SO_2, NO_x, and PM sources due to the lack of pollutant removal facilities. Although the SO_2 and NO_x emission control has been an important policy in China since 2010 and 2014, the emissions of civil boilers have not been effectively control due to the high cost (Zhang *et al.*, 2015).

Residential stationary sources including stoves, masonry heaters, and small-scaled boilers for heating and bathing are one of major emission sources of SO_2, NO_x, and PM due to the lack of pollutant control devices (Horák *et al.*, 2018). The power generation industry fueled with coal, gangue, coke oven gas, natural gas, and coal gas is a major anthropogenic SO_2, NO_x and PM source due to the combustion of fuel containing sulfur and nitrogen (Li *et al.*, 2016, 2017; Yan *et al.*, 2017). The coal-fired power plants (PPs) contribute approximately half of the total coal consumption in China and emit a large amount of air pollutants regionally and nationwide (Chen *et al.*, 2014). Previous studies carried out were mainly focused on the large-scaled coal-fired PPs, few studies were conducted on small-scaled gangue-, and gas-fired PPs (Li *et al.*, 2016, 2017; Dodla et al., 2017). Yan *et al.* (2017) reported higher NO_x, SO_2, and PM EFs were possessed by the gas-fired boilers compared with the coal-fired ones. As a world's largest coke producer, China contributed 68.6% to world's total coke production (447.78 Mt) in 2015 (Wang *et al.*, 2018). Due to the low energy utilization rate, complex process flows, abundant pollutant production links, coke manufacturing would be an important source of SO_2, NO_x, and PM (Huo *et al.*, 2012). In China, more than 80% of coking companies are independent small- and medium-scaled enterprises and distribute loosely across nation (CCIA, 2016). Previous studies were mainly focused on the POP emissions from the processes such as charging coal, pushing coke, and combustion of coke oven gas based on the data of one or few coke plants (Mu *et al.*, 2013, 2017; Liu *et al.*, 2009, 2013; Saikia, *et al.*, 2015). China has the first largest cement production in world and accounts for 60% the total world production in 2012 due to its fast urbanization (Chen *et al.*, 2015b). The total coal and electricity consumptions of Chinese cement industry in 2009 were 1.87×10^8 t and 1.38×10^9 kwh, resulted in the emission of 8.9×10^5 t of SO_2, 1.69×10^6 t of NO_x, and 3.58×10^6 t of PM (Mao *et al.*, 2012; Pang *et al.*, 2013).

A variety of expression methods of emission factors (EFs) have been documented elsewhere (Yao *et al.*, 2015; Yang *et al.*, 2017; Hsieh *et al.*, 2018). Hsieh *et al.* (2018) used the emitted pollutant mass per combusted fuel and generated electricity to calculate the EFs of PCDD/Fs for a municipal waste-fired PP. Yao *et al.* (2015) reported the NO_x EFs as pollutant mass per kilometer (g km^{-1}) for China III and IV in-use diesel trucks. Fachinger *et al.* (2017) discussed the EFs of PM_1, $PM_{2.5}$, and PM_{10} using pollutant mass per calorific value as mg MJ^{-1} under the influence of burning conditions and fuel types.

To our knowledge, few systematic and integrated EFs for SO_2, NO_x, and PM compiled for boilers with different purposes, fuels, produced outputs, scales, and generated power are currently available. In this study, the establishing of category-specific EFs of SO_2, NO_x, and PM were obtained by field measurements for various companies and the industries involved in small-scaled civil heating and bathing, power generation with different fuels and values of individual block power capacity (IBPC), and small- and medium- sized coke and cement manufacturing.

METHODS

In this study, 17 civil small-scales boilers (SCBs) for heating, bathing, and production, 13 coking companies, 15 power plants (PPs) (9 coal-fired PPs, 2 gangue-fired PPs, 1 coke oven gas-fired PP, 1 natural gas-fired PP, and 2 coal gas-fired PPs), and 8 cement making companies were field investigated and measured for their SO_2, NO_x, and PM EFs. All the factories were located at Shanxi province, China.

A flue gas analyzer (Laoying-3012H, Qingdao Laoying Environmental Science and Technology, Co., LtD.) was used for analysis of the flue gas temperature, concentrations of gaseous pollutants such as SO_2, NO_x, and CO, at the outlet of flue gas after the pollutant control devices in order to investigate the actual pollutants entered into atmospheric environment. At the same time, a pilot tube was applied to the measurement of velocity of flue gas and collection of particle matter (PM) in flue gas. The PM mass divided by sampling flue gas volume was the PM mass concentration. For quality assurance and quality control, the gas analyzers were calibrated with zero gas and targeted standard gases (NO, NO_2, SO_2 and O_2) prior to the first test of the day.

The coal compositions associated with proximate and ultimate analysis were obtained from field measurement or provided by local factories. The proximate and ultimate analysis of coal was conducted based on Chinese standard methods of GB/T-212-2008 and GB/T 476-2001.

Expression Mode of Emission Factor and Calculation Method

The emission amounts of SO_2, NO_x and PM were calculated as their mass concentration multiply by the total flue gas volume. The emission factors (EFs) were expressed in four ways and calculated using equation (1) to (4). EF_I (kg t^{-1}) was the pollutant mass per fuel mass consumed, EF_{II} was the pollutant mass per product mass (kg t^{-1} or g t^{-1}), EF_{III} reported in kg (10^6 yuan)$^{-1}$ or kg MY^{-1} was the pollutant mass per industrial output value, and EF_{IV} (kg $Mkwh^{-1}$) was the pollutant mass per generated millionaire kwh by a power plant.

$$EF_I = C_i \times V_f \times 1000 \quad \text{or } EF_I = \frac{C_i \times v \times 3600 \times \pi \times D^2}{4 \times S \times \rho} \tag{1}$$

Where EF_I is the EF expressed as pollutant mass per fuel consumption (kg t^{-1} or g t^{-1}), C_i is the pollutant mass concentration in flue gas (kg m^{-3}), V_f is the flue gas volume generated from combustion of 1 kg solid fuel (m^3 kg^{-1}), v is the velocity of flue gas (m s^{-1}), D is the diameter of chimney (m), S is the feed rate of gaseous fuel (Nm^3 h^{-1}), ρ is the mass density of gaseous fuel (t m^{-3}).

$$EF_{II} = \frac{C_i \times V_f \times m_F}{RMB} \text{ or } EF_{II} = \frac{C_i \times v \times \pi \times D^2 \times T \times 3600}{4 \times RMB} \tag{2}$$

Where EF_{II} is the EF expressed as pollutant mass per industrial output value (kg MY^{-1}), m_F is the annual amount of coal consumed by a factory (t a^{-1}), RMB is the annual total output value of a factory (10^6 yuan a^{-1}), T is the actual annual running time of a factory (h a^{-1}).

$$EF_{III} = \frac{C_i \times V_f \times m_F}{m_P} \tag{3}$$

Where EF_{III} is the pollutant mass per product mass (kg t^{-1}) and designated to access the EFs for coke making industry, m_P is the annual product mass (t a^{-1}).

$$EF_{IV} = \frac{C_i \times V_f \times m_F}{PG} \quad \text{or } EF_{IV} = \frac{C_i \times v \times \pi \times D^2 \times T \times 3600}{4 \times PG} \tag{4}$$

Where PG is the annual power generation for a power plant (10^6 kwh a^{-1}).

Determination of Flue Gas Volume from Combustion of Solid Fuel for Heat, Bath, and Power

The needed theoretical air volume for completely combustion of 1 kg of coal or gangue was calculated as following.

$$V_a^0=0.0889\ \omega(C_{ar})+0.2567\ \omega(H_{ar})+0.0333\ \omega(S_{ar})+0.0762\ \omega(N_{ar})-0.0333\ \omega(O_{ar}) \tag{5}$$

Where V_a^0 is the theoretical air volume for combustion of 1 kg of coal or gangue (m^3 kg^{-1}), $\omega(C_{ar})$ is the carbon content of coal or gangue (as received basis), $\omega(H_{ar})$ is the hydrogen content of coal or gangue (as received basis), $\omega(N_{ar})$ is the nitrogen content of coal or gangue (as received basis), and $\omega(O_{ar})$ is the oxygen content of coal or gangue (as received basis).

The theoretical flue gas volume is calculated by equation (6).

$$V_f^0 = V_{RO_2} + V_{H_2O}^0 + V_{N_2}^0 \tag{6}$$

Where V_f^0 is the theoretical flue gas volume generated from burning of 1 kg coal or gangue (m^3 kg^{-1}), V_{RO_2} is the sum of volume of CO_2, SO_2, and NO_2 (m^3 kg^{-1}), $V_{H_2O}^0$ is the volume of water vapor (the sum of combustion of hydrogen in coal or gangue, vaporization of water in coal or gangue, and vapor in air) (m^3 kg^{-1}), $V_{N_2}^0$ is the nitrogen volume in V_a^0 (m^3 kg^{-1}).

$$V_{RO_2} = V_{CO_2} + V_{H_2O} + V_{N_2} = 0.01867\omega(C_{ar}) + 0.007\omega(S_{ar}) + 0.0016\omega(N_{ar}) \quad (7)$$

$$V_{H_2O}^0 = 0.112\omega(H_{ar}) + 0.00124\omega(M_{ar}) + 0.0161V_a^0 \quad (8)$$

Where M_{ar} is the moisture content of coal.

$$V_{N_2} = 0.79V_a^0 \quad (9)$$

Finally the actually generated flue gas was calculated by equation (10). (10)

$$V_f = V_f^0 + (\alpha - 1)V_a^0 + 0.0161(\alpha - 1)V_a^0$$

Where α is the excess air coefficient, which is obtained from the investigation of factories.

Determination of Flue Gas Volume for Coking and Cement Industries

The flue gas for these two industries is not fully produced by fuel combustion. For coke making, the flue gas is generated from different processes including coal charging, coke pushing, coking and coke quenching, and fuel combustion. The flue gas volume can't be obtained as aforementioned method and should be calculated by equation (11).

$$V_f = \frac{v \times \pi \times D^2 \times T \times 3600}{CP} \quad (11)$$

Where V_f is the generated flue gas volume per annual produced coke or cement mass (m^3 kg^{-1}), T is the annual running time (h), CP is the annual production of cement or coke (kg a^{-1}).

RESULTS AND DISCUSSIONS

Emission of Air Pollutants of the Coal-fired Boilers for Bathing, Heating, and Production

(Table 1)

The emission amounts of pollutants from the SCBs were higher than those of large-scaled coal fired boilers due to the absence of pollutant RDs (Ma *et al.*, 2017a). **Table 1** listed the parameters for 17 civil coal-fired SCBs for heating, bath, and production. The coal consumptions were ranged from 30 to 70683 t a^{-1} for these 17 companies. The companies with coal consumption lessen than 1100 t a^{-1} were not equipped with SO_2 RDs. The removal rates for SO_2 RDs for the rest SCBs were ranged from 61% to 85%. The wet flue gas desulphurization (WFGD) technology was not used in these SCBs. The applied PM RDs in these SCBs contained fabric filters, water bath, and ceramic multi tubes. The 4 SCBs with the coal consumption as 30–400 t a^{-1} were not equipped with the PM RDs. Only 3 of 17 companies with high coal consumptions as 18250, 42000, and 70683 t a^{-1} were equipped with NO_x RDs including selective non catalytic reduction (SNCR) facility, low NO_x burner, and oxidation equipment.

Fig. 1 showed the EF_I values (reported in kg t^{-1}) for the SCBs applied in bath, heating, and production industries. The boilers with higher coal consumptions (Heating 15, 16, and 17) had the lower SO_2, NO_x, and PM EF_I values compared with the other 14 ones, possibly resulted from high pollutant removal rate of companies with high coal consumptions. The EF_I values for heating 15, 16, and 17 were ranged from 1.49 to 3.84 kg t^{-1} for SO_2, from 1.81 to 2.19 kg t^{-1} for NO_x, and from 0.532 to 3.68 kg t^{-1} for PM, respectively.

(Fig. 1)

The sulfur content and removal rate of SO_2 RDs were key influencing factors on the SO_2 emissions. The highest SO_2 EF_I value of 34.3 kg t^{-1} occurred at Heating 13, the high sulfur content (1%) of coal and no installed SO_2 RDs were the possible explanations. The following EF_I value of 34.0 kg t^{-1} was possessed by Heating 8 with 2% sulfur content and the lime used as desulphurizer. The rest boilers with sulfur contents in the range of 0.29%–0.60% had the SO_2 EF_I values ranged from 1.49 to 9.67 kg t^{-1} with the average as 5.72±2.55 kg t^{-1}. All the 17 civil SCBs were divided into two categories based on with or without SO_2 RDs. Class I was not equipped with SO_2 RDs and the 8 companies Heating 1, 2, 3, 6, 11, 12, 14, and Bath 10 were involved. Class II was equipped with SO_2 RDs and Heating 4, 15, 16, 17, bath 5, and Production 7, 9 were involved. The SO_2 EF_I values for Class I (3.23–9.67 kg t^{-1}, mean±SD: 6.90±2.31 kg t^{-1}) were higher than those of Class II (1.49 –7.65 kg t^{-1}, mean±SD: 4.37±2.33 kg t^{-1}).

The NO_x EF_I values for 17 companies were ranged from 1.81 to 9.68 kg t^{-1} with the average value as 3.16±1.72 kg t^{-1}. Only 3 of 17 companies were equipped with NO_x RDs such as SNCR, oxidation, and low NO_x burner. The NO_x EF_I values for these 3 factories (1.81–2.19 kg t^{-1}, mean±SD: 2.00±0.192 kg t^{-1}) were lower than those for the rest 14 ones without NO_x RDs (2.93–9.68 kg t^{-1}, mean±SD: 3.41±1.79 kg t^{-1}). The highest NO_x EF_I occurred at Heating 3 with the coal consumption as 310 t a^{-1}, its low combustion temperature and the high nitrogen content of coal (2.10%) are likely reasons for the high EF. Compared with SO_2 emission, the influence degree of generated vapor and coal consumptions of companies on NO_x was relatively light.

Except for 4 factories with low coal consumptions (30, 80, 280, and 400 t a^{-1}), 13 ones were all equipped with PM RDs including water bath, fabric filter, and wet method. The 4 factories without PM RDs possessed PM EF_I values as 22.5–27.5 kg t^{-1} and the mean value as 23.9±2.41 kg t^{-1}, which were significantly higher than those of 13 ones equipped with PM RDs (0.53–14.4 kg t^{-1}, mean±SD: 5.41±5.44 kg t^{-1}). Due to the influence of dust removal rate and running time of dust control devices, the large fluctuation of PM EF_I values occurred among 13 factories.

Emission of Air Pollutants from Power Plants

Although some advanced pollutant removal technologies were explored and improved in Chinese power plants, such as increasing generating capacity of individual block, adopt low NO_x burner, and adopt advanced air pollution control devices and technologies, the emissions of air pollutants were tremendous (Ma *et al.*, 2017a). The influence of fuel types and individual block power capacity (IBPC) on pollutant EFs should be discussed.

In this study, 15 power plants (PPs) including 1natural gas-fired PP, 1 coke oven gas-fired PP, 2 coal gas-fired PPs with IBPCs as 3 and 6 MW, 2 gangue-fired PPs with IBPCs as 135 and 25 MW, and 9 coal-fired PPs with IBPCs ranged from 6 to 600 MW. Besides the EF_I and EF_{III}, EF_{IV} expressed by pollutant mass per generated power capacity (reported in kg $Mkwh^{-1}$) was also used in PPs.

(Fig. 2)

Fig 2. showed the EF_{III} and EF_{IV} values for all the 15 PPs. For coal-, coal gas-, and gangue-fired PPs, generally the EF_{III} and EF_{IV} values decreased with the increase of their IBPCs. It should be mentioned, the EFs for coal-fired PPs had the decreasing trends from 6 MW to 330 MW and 600 MW PPs possessed slightly higher EFs than 330 MW ones. The coal-fired PPs with IBPCs as 25–135 MW possessed the highest EF_{III} values as 121–187, 141–448, and 36.5–101 kg MY^{-1} for SO_2, NO_x, and PM. The corresponding values were 25.6–148, 50.9–91.9, and 12.9–21.8 kg MY^{-1} for 300–330 MW PPs, while they were 85.4–100, 111–178, and 18.3–51.6 for 600 MW PPs.

Gas-fired PPs possessed higher NO_x EF_{III} values, and similar SO_2 and PM EF_{III} compared with the coal- and gangue-fired ones due to the lack of SO_2, NO_x, and PM RDs. For gas-fired PPs, the EF_{III} values (in kg MY^{-1}) were ranged from 31.4 to 184 (mean±SD: 120±65.2) for SO_2, 1090 to 6380 (mean±SD: 4630±2140) for NO_x, and 46.3 to 672 (mean±SD: 314±225), respectively. Yan *et al.* (2017) also reported the NO_x EFs for gas-fired boiler for Beijing was as high as 1.42–6.86 g m^{-3}. Gangue-fired PPs had the higher SO_2, NO_x, and PM EFs than coal-fired ones with the same IBPCs. For gangue-fired PPs, the 25 MW one possessed higher EF_{III} values than 135 MW one, they were 5900, 333, and 770 of SO_2, NO_x, and PM for 25 MW PP, and 157, 202, and 176 kg MY^{-1} for 135MW one. The high ash content in gangue and low removal rate of SO_2 and NO_x (0.00%) resulted in higher EFs of gangue-fired PPs. The highest SO_2 EF_{III} of 1520 kg MY^{-1} occurred at 6 MW coal-fired PP and the lowest value of 25.6 kg MY^{-1} was possessed by coal fired 330 MW PP.

While for PM, they were ranged from 12.8 kg MY^{-1} of coal-fired 300 MW PP to 3100 of coal-fired 6 MW PP.

The EF$_{IV}$ and EF$_{I}$ showed the same trends with the EF$_{III}$ **(Table 2)**. The higher NO$_x$ EF$_{IV}$ and EF$_{I}$ values (88.4–1640 kg Mkwh^{-1} and 1.29–19.1 kg t^{-1}) occurred at the gas-fired PPs due to the lack of RDs. The coal-fired 330 MW PP had the lowest NO$_x$ EF$_{IV}$ and EF$_{I}$ as 14.7 kg Mkwh^{-1} and 0.265 kg t^{-1}, respectively. For PM, the coal-fired 6 MW PP possessed the highest EF$_{IV}$ and EF$_{I}$ as 1150 kg Mkwh and 9.11 kg t^{-1}, while the lowest values occurred at 300 MW coal-fired PP as 3.03 kg Mkwh^{-1} and 0.061 kg t^{-1}, respectively. For SO$_2$, the gangue-fired 25 MW PP had the highest EF$_{IV}$ and EF$_{I}$ as 3620 kg Mkwh^{-1} and 16.7 kg t^{-1}, the lowest EF$_{I}$ and EF$_{IV}$ were possessed by a coal gas-fired 6 MW PP as 0.023 kg t^{-1} and a coal-fired 330 MW PP as 7.37 kg Mkwh^{-1}, respectively.

Among 9 coal-fired PPs, the 6 MW PP provided the higher pollutant EFs due to its relative low removal rate of pollutants. Except for 600 MW PPs, all the 3 classes of EFs decreased in the order of 6 MW>25 MW>100 MW>135 MW>300/330MW. The EFs for SO$_2$ and PM of 600 MW PP were similar to those of 300–330 MW, while they possessed higher NO$_x$ EFs than 135 MW PP due to their high combustion temperature. The coal-fired 6 MW PP possessed the highest EF$_{III}$ and EF$_{IV}$ of SO$_2$, NO$_x$, and PM as 1520, 323, and 3100 kg MY^{-1}, and 561, 120, and 1150 kg Mkwh^{-1}. Also the 6 MW coal-fired PP possessed the highest SO$_2$ and PM EF$_{I}$ as 4.46 and 9.11 kg t^{-1}. But for NO$_x$ EF$_{I}$ values for the coal-fired PPs, two 600 MW PPs had the highest levels as 1.24 and 2.12 kg t^{-1}.

The significantly difference among differently fueled PPs or different IBPC groups of coal-fired PPs was mainly influenced by pollutant removal rate, characteristic of fuel, and combustion conditions (Chen *et al*., 2014; Li *et al*., 2016, 2017; Xu *et al*. 2017b).

Chen *et al*. (2014) indicated that units higher than 300MW consumed 75% of coal, while the emitted pollutants contributed only 46%, 58%, 55%, and 63.2% to SO$_2$, NO$_x$, PM and PM$_{2.5}$. Xu *et al*. (2017b) suggested the generator factors (GFs) (in g kg^{-1}) of pollutants for PPs decreased with the decrease of IBPC values, and reported NO$_x$ for different IBPC groups (in MW) as 450-749, 250-449, 150-249, 75-149, 35-74, 20-34, 9-19, and ≤8 were 10.11, 9.33, 8.36, 8.13, 6.88, 6.54, 5.14, and 5.04 g m^{-3}, respectively, while their actual NO$_x$ emissions showed the reverse trend (Xu *et al*., 2017b). Ma *et al*. (2017a) also put forward that the pollutant EFs decreased with the increase of IBPC values of PPs. Even if no any dust removal devices, the PM$_{2.5}$ EFs could also decreased from 153 g t^{-1} for 100 MW PP to 123 g t^{-1} for 300 MW PP.

(Table 2)

Recently, fine particles such as $PM_{2.5}$ and PM_{10} were more concerned than coarse ones due to their seriously adverse health effects (Ma *et al.*, 2017a, 2017b). In regard to the lack of data from field monitoring of $PM_{2.5}$ and PM_{10}, the calculated data were given and showed as following:

$$\mathrm{EF}_{\mathrm{PM}_{2.5}\ \mathrm{or}\ \mathrm{PM}_{10}} = \mathrm{EF}_{\mathrm{PM}} \times (\text{mass contribution of } \mathrm{PM}_{2.5} \text{ or } \mathrm{PM}_{10} \text{ to total PM}) \quad (12)$$

Klimont *et al.* (2002) reported the $PM_{2.5}$ and PM_{10} fractions as 6% and 23% for the pulverized coal (PC) boiler, while they were 7% and 29% for the circulating fluidized bed (CFB) boiler. Among 9 coal-fired and 2 gangue-fired PPs, 8 coal-fired PPs were equipped with PC boilers and the other 3 PPs possessed the CFB boilers. So the $PM_{2.5}$ and PM_{10} EFs were calculated by equation (12).

(Fig. 3)

The $PM_{2.5}$ and PM_{10} EFs (expressed as EF_I, EF_{III}, and EF_{IV}) had the same trends with PM EFs **(Fig. 3 and Table 3)**. For $PM_{2.5}$ EFs, the coal-fired 6 MW PP possessed the highest value as 217 kg MY^{-1} and 80.2 kg $MkWh^{-1}$, the lowest values occurred at 300 MW as 0.767 kg MY^{-1} and 330 MW as 0.182 kg $MkWh^{-1}$. For PM_{10}, the highest EFs were possessed by the 6 MW coal-fired PP as 898 kg $MkWh^{-1}$ and 323 kg $MkWh^{-1}$, while the lowest values occurred at 300 MW coal-fired PP as 2.94 kg MY^{-1} and 330 MW coal-fired PP as 0.698 kg $MkWh^{-1}$ **(Fig .3)**.

The gangue-fired PPs possessed higher $PM_{2.5}$ and PM_{10} EFs (EF_{III} and EF_{IV}) values than coal fired PPs with the same IBPC values, possibly resulted the high ash content in fueled gangue.

The highest EF_I of 638 g t^{-1} for $PM_{2.5}$ and 3640 g t^{-1} for PM_{10} were possessed by a coal-fired PP with lowest IBPC as 6 MW **(Table 3)**. The lowest EF_I occurred at 300 MW PP, which were 3.66 and 14.0 g t^{-1} for $PM_{2.5}$ and PM_{10}, which were similar to the documented value (Ma *et al.*, 2017a). They were 14 g t^{-1} for 300 MW PP with an electrostatic precipitator (ESP) and 3 g t^{-1} for 300 MW PP with an improved ESP (Ma *et al.*, 2017a). The $PM_{2.5}$ EFs for coal- and gangue-fired PPs were far lessen than those of household coal stoves. Chen *et al.* (2015a) measured the $PM_{2.5}$ EFs (reported in g kg^{-1}) for 20 Chinese combinations of coal and stoves, and they were 4.25 and 1.44 for bituminous and anthracite coal, respectively.

(Table 3)

Emission of Air Pollutants from Coke Making Industries

In this study, 22 medium- and small-sized coke making factories fueled with coke oven gas were investigated to access their pollutant EF_{II} and EF_{III} values. The annual coke outputs were ranged from 2.10×10^4 to 2.31×10^6 tons. All the 22 factories were equipped with bag filter to collect the dust and the removal rates ranged from 68.9% to 98.4%. Among 22 factories, only 5 ones equipped with SCR devices to eliminated NO_x with the removal rate as 40.1%–79.8%. The significantly fluctuation of the SO_2 removal rate (0.00% to 98.1%) occurred among these factories. The SO_2 removal measures contained wet and dry FGD methods, and the desulphurization reagents were NaOH, $Ca(OH)_2$, NH_3, and Na_2CO_3.

(Fig. 4)

The EF_{II} and EF_{III} values for 22 coking companies were not correlated with their coke productions and industrial outputs because their flue gas was not fully emitted from combustion process **(Fig. 4)**. The heat for raw coal pyrolysis originated from the combustion of cycled coke oven gas, the mass of fuel is difficult to determined, so EF_I can't be used in coking industry. **Fig. 4** showed the EFs of SO_2, NO_x, and PM expressed by EF_{II} as kg (t coke)$^{-1}$ and EF_{III}. For SO_2, EF_{II} and EF_{III} values were ranged from 0.098 to 0.170 kg (t coke)$^{-1}$ and 3.79 to 27.8 kg MY^{-1} for 22 companies. EF_{II} and EF_{III} values of NO_x were in the range of 0.402–1.22 kg (t coke)$^{-1}$, and 27.8–167 kg MY^{-1}, respectively. EF_{II} and EF_{III} values of PM were in the range of 0.063–1.08 kg (t coke)$^{-1}$, and 7.71–148 kg MY^{-1}, respectively. Compared with SO_2, NO_x and PM have larger fluctuation among 22 companies under the influence of their pollutant removal rates, ash contents of coal and combustion conditions.

Table 4 listed the parameters of 5 companies with byproduct as tar and crude benzene. For these 5 companies, SO_2 EF_{II} values were ranged from 2.38 to 5.14 kg (t tar)$^{-1}$ and 9.33 to 18.8 kg (t benzene)$^{-1}$, NO_x EF_{II} values were in the range of 9.82–29.3 kg (t tar)$^{-1}$ and 38.5–111 kg (t benzene)$^{-1}$, and those of PM were in the range of 3.96–26.1 kg (t tar)$^{-1}$ and 14.5–98.7 kg (t benzene)$^{-1}$.

(Table 4)

The EFs of NO_x were higher than those of SO_2 and PM, possibly resulted from the high removal rate of SO_2 and PM by desulfurization and dust removal devices.

Emission Factors for Pollutants from Cement Production Industry

Chen *et al*. (2015b) used the life-cycle assessment (LCA) method to estimate the pollutant emissions of cement industry. The PM emission from cement industry was associated with mineral matter and coal combustion (Mari *et al*., 2016). The PM associated with raw material grinding and coal combustion entered the bag filter and discharged through induced fan.

In this study, 6 cement making companies including 2 small- and 4 medium-scaled ones with the cement production as 16,400–1,464,170 t a^{-1} were investigated for SO_2, PM and NO_x emissions. The coal consumptions for 6 factories were ranged from 131 to 123,570 t a^{-1} with the sulfur and ash contents of coal were 0.2%–0.8% and 7.6%–26.04%, respectively.

All the 6 factories applied bag filter to remove PM with the removal rates ranged from 72.3% to 98.8% due to the fluctuation of running time and running conditions of PM RDs. It should be mentioned, all the 6 cement factories were not equipped NO_x removal devices, and only 2 factories were equipped with SO_2 removal devices.

EF_I, EF_{II}, and EF_{III} were used to express the pollutant EFs for these 6 companies. **Fig. 5** listed the calculation results of EF_I value for SO_2, NO_x, and PM. Generally the SO_2 EF_I values (0.964–10.2 kg t^{-1}) were not correlated with the coal consumptions and cement outputs. PM EF_I values were negatively correlated with the consumed coal amounts and cement output. The factory with lowest consumed coal (131 t a^{-1}) possessed the highest PM EF_I as 220 kg t^{-1}, while the lowest PM EF as 1.26 kg t^{-1} occurred at factory with higher consumed coal (75,000 t a^{-1}). The PM EFs were higher than those of coal-, gangue-, and gas-fired power plants. The factories with the higher cement output possessed the higher NO_x EFs result from their high combustion temperature and the other combustion conditions. The 2 factories with highest coal consumptions as 75,000 and 123,570 t a^{-1} had the highest NO_x EF_I values as 16.9 and 15.2 kg t^{-1}, while the lowest NO_x EF_I values of 2.88 kg t^{-1} was possessed by factory with lower consumed coal as 7,167 t a^{-1}.

Unlike EF_I, the EF_{II} and EF_{III} were not correlated with production of cement and value of industrial output, possibly resulted from the differences of cement price, production processes, and investment of environmental protection **(Table 5)**.

(Fig. 5)

(Table 5)

CONCLUSIONS

In this study, 17 civil SCBs for heating, bathing, and production, 13 coke making companies, 15 power plants (PPs) (9 coal-fired PPs, 2 gangue-fired PPs, 1 coke oven gas-fired PP, 1 natural gas-fired PP, and 2 coal gas-fired PPs), and 8 cement making companies were field investigated and measured for their SO_2, NO_x, and PM EFs. All the investigated factories were located at Shanxi and province, China.

1) Among 17 civil SCBs, 4, 14, and 10 SCBs were not equipped with PM, NO_x, and SO_2 RDs, respectively. Generally the SO_2, NO_x, and PM EFs decreased with the increase of coal consumptions. The 3 civil SCBs with highest coal consumptions possessed the lower EF_I values, they were ranged from 1.49 to 3.84 kg t^{-1} for SO_2, from 1.81 to 2.19 kg t^{-1} for NO_x, and from 0.532 to 3.68 kg t^{-1} for PM, respectively.

The NO_x EF_I values (1.81–2.19 kg t^{-1}, mean±SD: 2.00±0.192 kg t^{-1}) for 3 factories equipped with NO_x RDs, which were lower than those for the rest 14 ones without NO_x RDs (2.93–9.68 kg t^{-1}, mean±SD: 3.41±1.79 kg t^{-1}). Sulfur content of coal and SO_2 removal rate were key influencing factors on its EF_I. The highest SO_2 EF_I of 34.3 kg t^{-1} was possessed by a company with 1% sulfur content and no installed RDs. The 4 companies without PM RDs possessed the average PM EF_I values as 23.9±2.41 kg t^{-1}, which were higher than that of 13 factories with equipped dust removal devices as 5.41±5.44 kg t^{-1}.

2) For coal-, coal gas-, and gangue-fired power plants (PPs), generally the EF_I, EF_{III}, and EF_{IV} values decreased with the increase of their IBPC values. Gas-fired PPs possessed higher NO_x EFs, and similar SO_2 and PM EFs compared with coal- and gangue-fired PPs due to the lack of SO_2, NO_x, and PM RDs. Gangue-fired PPs possessed higher pollutant EF_I, EF_{III}, and EF_{IV} values than coal-fired PPs with same IBPC values. Except for 600 MW PPs, EF_I, EF_{III}, and EF_{IV} values for coal-fired PPs decreased in the order of 6 MW>25 MW>100 MW>135 MW>300/330MW. The EFs for SO_2 and PM of 600 MW coal-fired PP were similar to those of 300–330 MW, while they possessed higher NO_x EFs than 135 MW coal-fired PP due to its high combustion temperature. EF_I, EF_{III}, and EF_{IV} values of $PM_{2.5}$ and PM_{10} showed the same trends with those of PM.

3) The EF_{II} and EF_{III} values for 22 coking companies were not correlated with the coke productions and industrial outputs because their flue gas was not fully emitted from combustion process.

4) Generally the SO_2 EF_I values (0.964–10.2 kg t^{-1}) were not correlated with the coal consumptions and cement outputs. PM EF_I values were negatively correlated with the consumed coal amounts and cement outputs. The factory with lowest consumed coal (131 t a^{-1}) possessed the highest PM EF as 220 kg t^{-1}, while the lowest PM EF as 1.26 kg t^{-1} occurred at factory with higher consumed coal (75,000 t a^{-1}). The PM EF_I values were higher than those of coal-, gangue-, and gas-fired power plants. The factories with high cement output possessed the high NO_x EFs result from their high combustion temperature. EF_{II} and EF_{III} values were not correlated with cement productions and coal consumptions.

ACKNOWLEDGEMENTS

This study was supported by the Fundamental Research Funds for the Central Universities (2017MS142) and National Natural Science Foundation of China (21407048),

REFERENCES

Annamalai, M., Dhinesh, B., Nanthagopal, K., SivaramaKrishnan, P., Isaac Joshua Ramesh Lalvani, J., Parthasarathy, M., Annamalai, K., 2016. An assessment on performance, combustion and emission behavior of a diesel engine powered by ceria nanoparticle blended emulsified biofuel. Energy Convers. Manag. 123:372–380.

China Coking Industry Association (CCIA) (2016b). List of enterprises that conform to, change and cancel the name of the announcement of the coking industry. http://www.cnljxh.com/zcfg/2017/1/13/16000136000j83 5i.html (in Chinese).

Chen, L.H., Sun, Y.Y., Wu, X.C., Zhang, Y.X., Zheng, C.H., Gao, X. and Cen, K.F. (2014). Unit-based emission inventory and uncertainty of coal-fired power plants. *Atmos. Environ.* 99: 527–535.

Chen, Y.J., Tian, C.G., Feng, Y.L., Zhi, G.R., Li, J. and Zhang, G. (2015a). Measurements of emission factors of $PM_{2.5}$, OC, EC, and BC for household stoves of coal combustion in China. *Atmos. Environ.* 109:190–196.

Chen, W., Hong, J.L. and Xu, C.Q. (2015b). Pollutants generated by cement production in China, their impacts, and the potential for environmental improvement. *J. Clean. Prod.* 103: 61–69.

Cheng, J., Zhang, Y.S., Wang,T., Xu, H., Norris, P. and Pan, W.P. (2018). Emission of volatile organic compounds (VOCs) during coal combustion at different heating rates. Fuel, 225: 554–562.

Dodla, V.B.R., Gubbala, C.S. and Desamsetti, S. (2017). Atmospheric dispersion of $PM_{2.5}$ precursor gases from two major thermal power plants in Andhra Pradesh, India. *Aerosol Air Qual. Res.*17:381–393.

Fachinger, F., Drewnick, F., Gieré, R. and Borrmann, S. (2017). How the user can influence particulate emissions from residential wood and pellet stoves: Emission factors for different fuels and burning conditions. *Atmos. Environ.* 158: 216–226.

Fang, M., Chan, C. and Yao, X. (2009). Managing air quality in a rapidly developing nation: China. *Atmos. Environ.* 43: 79–86.

Horák, J., Kuboňová, L., krpec, K., Hopan, F., Kubesa, P., Koloničný, J. and Plachá, D. (2018). A comparison of PAH emission sampling methods (cyclone, impactor) in particulate and gaseous phase. *Aerosol Air Qual. Res.*18: 849–855.

Hsieh, Y.K., Chen, W.S., Zhu, J.N. and Huang, Q.L. (2018). Characterization of polychlorinated dibenzo-p-dioxins and dibenzofurans of the flue gases, fly ash and bottom ash in a municipal solid waste incinerator. *Aerosol Air Qual. Res.*18: 421–432.

Huo, H., Lei, Y., Zhang, Q., Zhao, L. and He, K. (2012). China's coke industry: Recent policies, technology shift, and implication for energy and the environment. Energy Policy 51: 397.

Kiros, F., Shakya, K.M., Rupakheti, M., Regmi, R.P., Maharjan, R., Byanju, R.M., Naja, M., Mahata, K., Kathayat, B. and Peltier, E. (2016). Variability of anthropogenic gases: nitrogen oxides, sulfur dioxide, Ozone and ammonia in Kathmandu Valley, Nepal. *Aerosol Air Qual. Res.*16:3088–3401.

Klimont, Z., Streets, D.G., Gupta, S., Cofala, J., Fu, L.X. and Ichikawa, Y. (2002). Anthropogenic emissions of non-methane volatile organic compounds in China. *Atmos. Environ.* 36:1309–1322.

Li, Z.Y., Chen, L., Liu, S.T., Ma, H.Q., Wang, L., An, C.X. and Zhang, R.L. (2016). Characterization of PAHs and PCBs in fly ashes of eighteen coal-fired power plants. *Aerosol Air Qual. Res.*16: 3175–3186.

Li, Z.Y., Ji, Y.Q., Ma, H.Q., Zhao, P., Zeng, X.C., Liu, S.T., Jiang, Y.J., Wang, L., Liu, A.Q., Gao, H.Y., Liu, F.D. and Mwangi, J.K. (2017). *Aerosol Air Qual. Res.*17: 1105–1116.

Liu, G.R., Zheng, M.H., Ba, T., Liu, W.B. and Guo, L. (2009). A preliminary investigation on emission of polychlorinated dibenzo-p-dioxins/dibenzofurans and dioxin-like polychlorinated biphenyls from coke plants in China. *Chemosphere*, 75: 692–695.

Liu, G.R., Liu, W.B., Cai, Z.W. and Zheng, M.H. (2013). Concentrations, profiles, and emission factors of unintentionally produced persistent organic pollutants in fly ash from coking processes. *J. Hazard. Mater.* 261:421–426.

Liu, F., Zhang, Q., Tong, D., Zheng, B., Li, M., Huo, H. and He, K.B. (2015). High-resolution inventory of technologies, activities, and emissions of coal-fired power plants in China from 1990 to 2010. *Atmos. Chem. Phys.* 15: 18787–18837.

Liu, H.B., Zhang, Z.X., Li, Q., Chen, T.H., Zhang, C.G., Chen, D., Zhu, C.Z. and Jiang, Y. (2017). Novel methods for preparing controllable nanoporous α-Fe_2O_3 and its reactivity to SCR de-NO_x. *Aerosol Air Qual. Res.*17: 1898–1908.

Ma, Z.Z., Li, Z., Jiang, J.K., Deng, J.G., Zhao, Y., Wang, S.X. and Duan, L. (2017a). $PM_{2.5}$ emission reduction by technical improvement in a typical coal-fired power plant in China. *Aerosol Air Qual. Res.*17: 636–643.

Ma, Q.X., Wu, Y.F., Tao, J., Xia, Y.J., Liu, X.Y., Zhang, D.Z., Han, Z.W., Zhang, X.L. and Zhang, R.J. (2017b). Variation of chemical composition and source apportionment of $PM_{2.5}$ during winter haze episodes in Beijing. *Aerosol Air Qual. Res.*17: 2791–2803.

Mari, M., Sánchez-Soberó, F., Audí-Miró, C., Van Drooge, B.L., Soler, A., Grimalt, J.O. and Schuhmacher, M. (2016). Source apportionment of inorganic and organic PM in the ambient air around a cement plant: assessment of complementary tools. *Aerosol Air Qual. Res.*16: 3230–3242.

Mao, Z.W., Yang, R.S. and Gan, H. (2012). Study on denitrification technology in cement kiln. *China Cem.* 5: 56–58.

Mu, L., Peng, L., Cao, J.J., He, Q.S., Li, F., Zhang, J.Q., Liu, X.F. and Bai, H.L. (2013). Emissions of polycyclic aromatic hydrocarbons from coking industries in China. *Particuology*, 11: 86–93.

Mu, L., Peng, L., Liu, X.F., He, Q.S., Bai, H.L., Yan, Y.L. and Li, Y.H. (2017). Emission characteristics and size distribution of polycyclic aromatic hydrocarbons from coke production in China. *Atmos. Res.* 197:113–120.

Pang, J., Shi, Y.C., Feng, X.Z., Liu, J. and Sun, W.L. (2013). Analysis on impacts and coabatement effects of implementing the low carbon cement standard. Progress. *Inquisit. Mutat. Clim.* 9: 275–283 (in Chinese).

Pascal, M., Corso, M., Chanel, O., Declercq, C., Badaloni, C., Cesaroni, G., Henschel, S., Meister, K., Haluza, D., Martin-Olmedo, P. and Medina, S. (2013). Assessing the public health impacts of urban air pollution in 25 European cities: Results of the Aphekom project. *Sci. Total Environ.* 449: 390–400.

Saikia, J., Saikia, P., Boruah, R. and Saikia, B.K. (2015). Ambient air quality and emission characteristics in and around a non-recovery type coke oven using high sulphur coal. *Sci. Tot. Environ*. 530–531: 304–313.

Wang, K., Tian, H.Z., Hua, S.B., Zhu, C.Y., Gao, J.J., Xue, Y.F., Hao, J.M., Wang, Y. and Zhou, J.R. (2016). A comprehensive emission inventory of multiple air pollutants from iron and steel industry in China: temporal trends and spatial variation characteristics. *Sci. Total Environ*. 559: 7–14.

Wang, S.G. and Chen, B. (2016). Accounting of SO_2 emissions from combustion in industrial boilers. *Energy Procedia.* 88:325–329.

Wang ,Y., Cheng, K., Tian, H.Z., Yi, P. and Xue, Z.G. (2018). Analysis of reduction potential of primary air pollutant emissions from coking industry in China. *Aerosol Air Qual. Res.*18:533–541.

Xu, J.Y., Jiang, H., Zhao, H.R. and Stephens, B. (2017a). Mobile monitoring of personal NO_x exposures during scripted daily activities in Chicago, IL. *Aerosol Air Qual. Res.*17:1999–2009.

Xu, Y., Hu, J.L., Ying, Q., Hao, H.K., Wang, D.X. and Zhang, H.L. (2017b). Current and future emissions of primary polluatants from coal-fired power plants in Shaanxi, China. *Sci. Tot. Environ.* 595: 505–514.

Yan, X., Song, G.W., Yan, J., Luo, Z.Y., Sun, X.S., Wei, C.W., Zhang, R., Li, G.H., Ding, Q. and Zhang, D. (2017). Emission characteristics of gas-fired boilers in Beijing city, China: category-specific emission factor, emission inventory, and spatial characteristics. *Aerosol Air Qual. Res.*17:1825–1836.

Yang, X.Y., Liu, S.J., Xu, Y.S., Liu, Y., Chen, L.J., Tang, N. and Hayakawa, K. (2017). Emission factors of polycyclic and nitro-polycyclic aromatic hydrocarbons from residential combustion of coal and crop residue pellets. *Environ. Pollut.* 231:1265–1273.

Yao, Z.L., Wu, B.B., Wu, Y.N., Cao, X.Y. and Jiang, X. (2015). Comparison of NO_x emissions from China III and China IV in-use diesel trucks based on-road measurements. Atmos. Environ. 123:1–8.

Zhang, Q.Q., Wang, Y., Ma, Q., Xie, Y. and He, K. (2015). Regional differences in Chinese SO2 emission control efficiency and policy implications. *Atmos. Chem. Phys.* 15: 4083–4115.

Zhao, Y., Zhou, Y.D., Qiu, L.P. and Zhang, J. (2017). Quantifying the uncertainties of China's emission inventory for industrial sources: From national to provincial and city scales. *Atmos. Environ.* 165: 207–221.

Zhong, Z.M., Sha, Q.E., Zheng, J.Y., Yuan, Z.B., Gao, Z.J., Ou, J.M., Zheng, Z.Y., Li, C. and Huang, Z.J. (2017). Sector-based VOCs emission factors and source profiles for the surface coating industry in the Pearl River Delta region of China. Sci. Tot. Environ. 583:19–28.

Table Captions

Table 1

Emissions of SO_2, NO_X and PM for 17 civil coal-fired small scale heating boilers.

Table 2

EF_I values of SO_2, NO_x, and PM for 15 power plants, kg (t coal/gas/gangue)$^{-1}$.

Table 3

EF_I values of $PM_{2.5}$ and PM_{10} for 11 power plants, g (t coal/gangue)$^{-1}$

Table 4

Annual raw material consumption and product output for 5 companies with byproduct as crude benzene and tar

Table 5

EF_{II} and EF_{III} values for 6 cement making companies

Table 1 Emissions of SO_2, NO_X and PM for 17 civil coal-fired small scale heating boilers

Industry type	S_{ad} (%)	A_{ad} (%)	Vapor (t h^{-1})	Coal consumption (t a^{-1})	De-SO_2	De-NO_x	Dust removal	SO_2 (t a^{-1})	NOx (t a^{-1})	PM (t a^{-1})
Heating1	0.2	15.5	4	1100	No	No	Fabric Filter	4.7	3.23	2.7
Heating2	0.5	17	4	1027.5	No	No	Fabric Filter	8.22	3.02	2.79
Heating3	0.6	17	2	310	No	No	Wet	1	3	1
Heating4	0.45	17.6	2×80	24000	Double Alkali	No	Fabric Filter	183.6	70.56	12.8
Bath5	0.3	18	10	2000	Lime	No	Water bath	10.20	5.88	5.85
Heating6	0.34	18	1	45	No	No	Water bath	0.26	0.13	0.65
Production7	0.3	15.5	4	800	Lime	No	Ceramic multi tube	4.08	2.35	6.2
Heating8	2	18	10	450	Lime	No	Wet	15.30	1.32	6.47
Production9	0.3	18	10	450	Lime	No	Water bath	2.60	1.32	6.47
Bath10	0.5	17	4	1100	No	No	Fabric Filter	8.22	3.02	2.79
Heating11	0.3	18	10	400	No	No	No	2.94	1.18	9.01
Heating12	0.3	18	5	280	No	No	No	2.64	0.82	6.40
Heating13	1	20	1	80	No	No	No	2.74	0.24	2.20
Heating14	0.3	18	0.35	30	No	No	No	0.29	0.09	0.68
Heating15	0.29	14	150	70683	Ca injection in furnace	LNC in CFB	Fabric Filter	105.29	127.84	58.61
Heating16	0.3	23	4×35+3×20	42000	Double Alkali	Oxidation	Water bath	161.24	83.47	154.58
Heating17	0.3	11	4×20	18250	Double Alkali	SNCR	Wet	29.6	40	9.7

LNC in CFB: Low NO_x combustion in a circulating fluidized bed

Table 2. EF_I values of SO_2, NOx, and PM for 15 power plants, kg (t coal/gas/gangue)$^{-1}$

Fuel	Coal Fired									Gangue		Gas			
												NG[a]	COG[b]	CG[c]	CG[c]
MW	6	25	100	135	300	300	330	600	600	135	25	3	3	6	6
SO_2	4.46	1.23	0.622	0.713	0.712	0.116	0.133	0.698	0.580	0.470	16.7	0.136	0.550	0.023	0.148
NOx	0.950	0.928	2.30	0.690	0.441	0.383	0.265	1.24	2.12	0.607	0.941	4.73	19.1	1.29	5.15
PM	9.11	0.239	0.518	0.200	0.061	0.093	0.098	0.128	0.350	0.530	2.18	0.200	0.807	0.182	0.218

[a] Natural gas; [b] Coke oven gas; [c] Coal gas

Table 3. EF_I values of $PM_{2.5}$ and PM_{10} for 11 power plants, g (t coal/gangue)$^{-1}$

Fuel	Coal									Gangue	
MW	6	25	100	135	300	300	330	600	600	135	25
$PM_{2.5}$	638	16.7	36.3	12.0	3.66	5.58	5.88	7.68	21.0	37.1	153
PM_{10}	2640	69.3	150	46.0	14.0	21.4	22.5	29.4	80.5	154	632

Table 4. Annual raw material consumption and product output for 5 companies with byproduct as crude benzene and tar

Company	Raw coal (10^5 t)	Coke oven gas (10^4 t)	Coke output (10^5 t)	Tar (10^3 t)	Crude benzene (10^3 t)	De-NOx (%)	De-PM (%)	De-SO_2 (%)	SO_2 (t)	NO_x (t)	PM (t)	¥ Output (10^9yuan)
1	2.66	2.39	1.90	6.27	1.46	0	94.8	20.5	23.3	76.6	79.0	2.30
2	13.1	11.9	9.26	30.6	8.38	0	98.4	94.5	157	570	121	7.65
3	2.56	1.81	1.90	5.50	1.85	54.7	94.9	45.7	519	915	78.8	1.43
4	15.4	7.41	10.2	42.3	11.2	39.3	86.5	97.6	125	1240	1110	7.45
5	6.00	5.32	4.54	17.8	4.67	1.5	94	97.5	56.6	442	220	4.30

Table 5. EF_{II} and EF_{III} values for 6 cement making companies

Cement output, t a^{-1}	EF_{II}, g t^{-1}			Output, 10^4 yuan	EF_{III}, kg (10^4 yuan)$^{-1}$		
	SO_2	NOx	PM		SO_2	NOx	PM
16,399	38.3	23.5	1750	200	3.14	1.93	144
32,000	116	661	152	400	3.50	19.9	4.56
422,300	88.9	48.1	317	6,800	5.62	3.04	20.0
430,000	77.1	22.2	377	14,000	6.17	1.78	30.2
2,300,000	97.4	708	289	22,568	9.65	70.2	28.7
2,648,580	88.7	552	292	26,732	9.04	56.2	29.8

Figure Captions

Fig. 1.

EF_I values for 17 small-scaled boilers for bath, heating, and production industries.

Fig. 2.

EF_{III} and EF_{IV} of pollutants for 15 PPs based on power capacity and industrial output.

Fig. 3.

EF_{III} and EF_{IV} values of $PM_{2.5}$ and PM_{10} from coal- and gangue-fired power plants.

Fig. 4.

EF_{II} and EF_{III} values of SO_2, NOx, and PM for 22 coke making companies.

Fig. 5.

EF_I values of SO_2, NOx, and PM for 6 cement making companies.

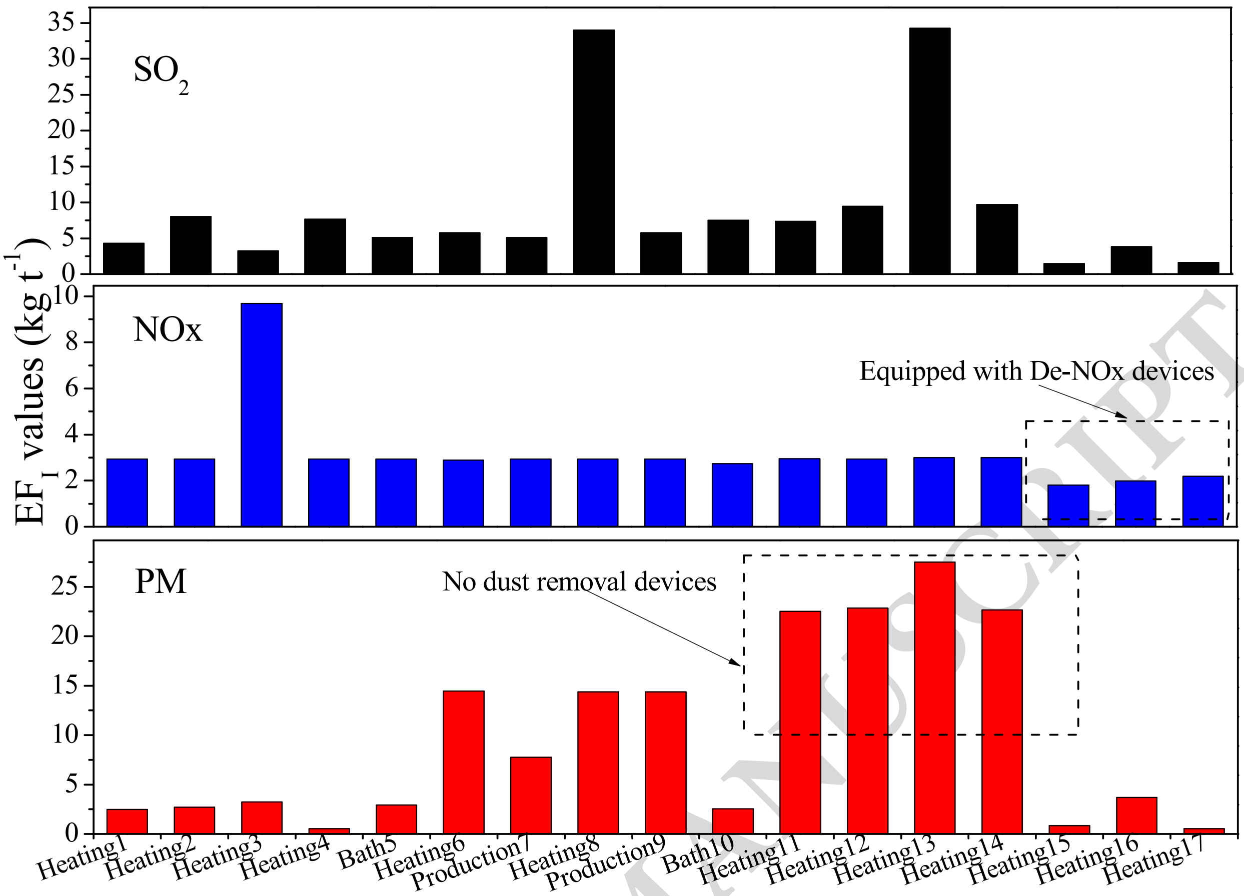

Fig. 1. EF$_I$ values for 17 small-scaled boilers for bath, heating, and production industries

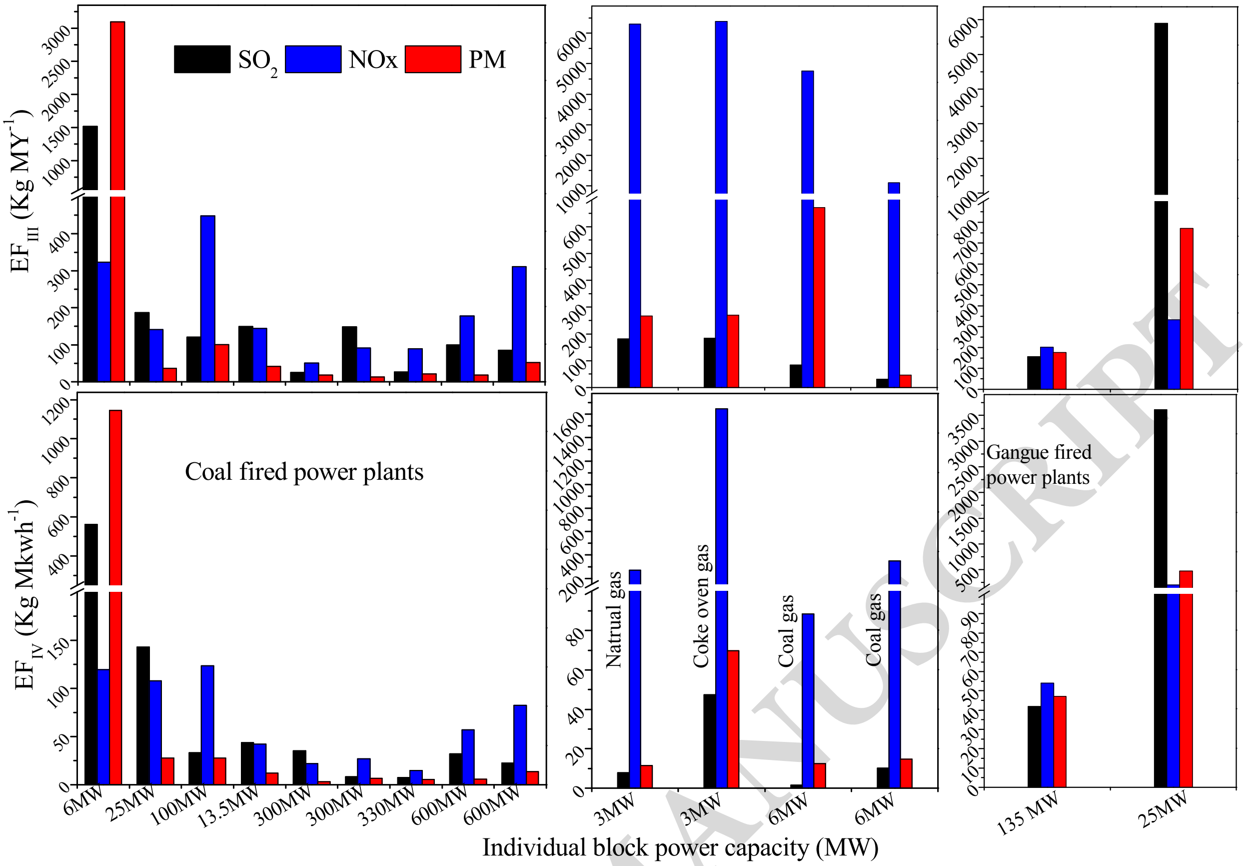

Fig 2. EF$_{III}$ and EF$_{IV}$ of pollutants for 15 PPs based on power capacity and industrial output

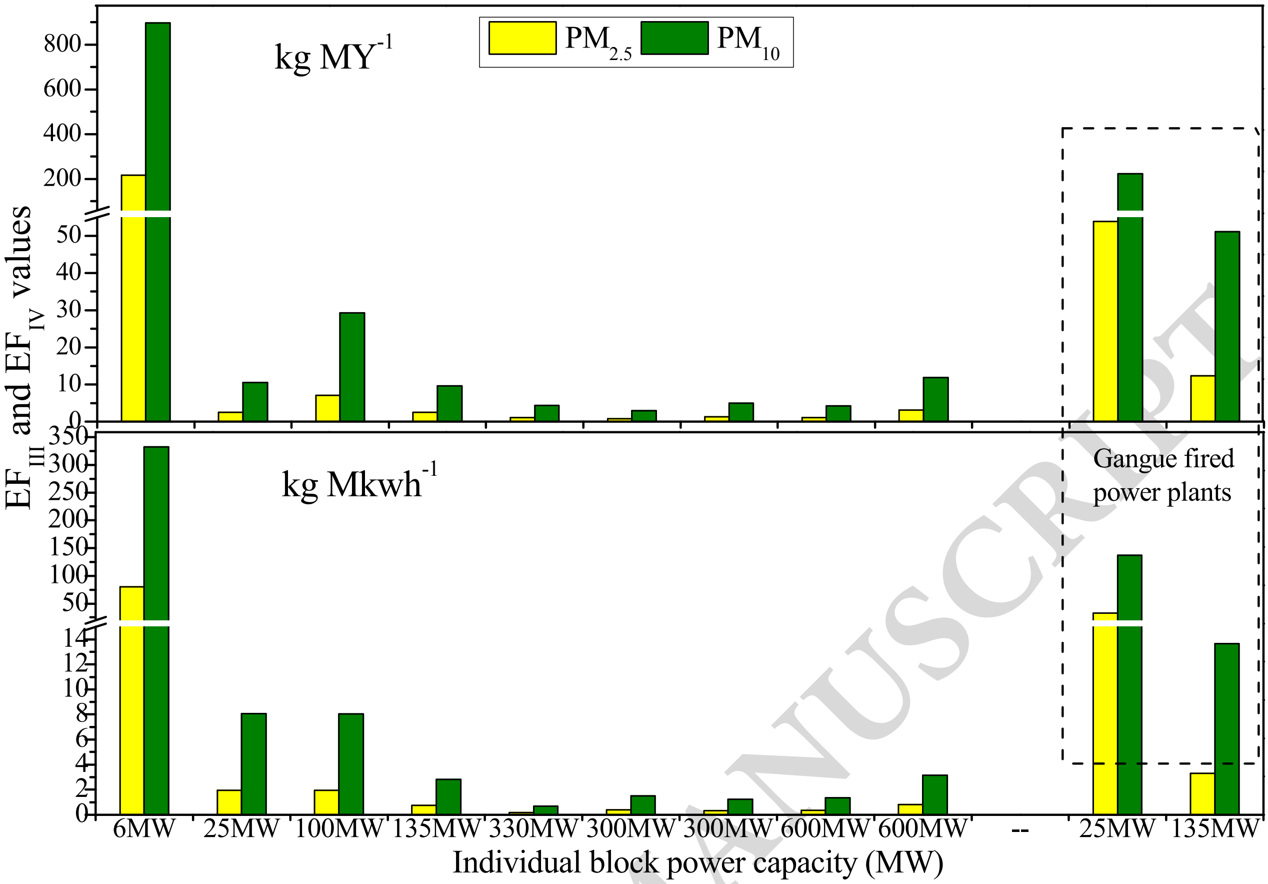

Fig. 3. EF$_{III}$ and EF$_{IV}$ values of PM$_{2.5}$ and PM$_{10}$ from coal- and gangue-fired power plants

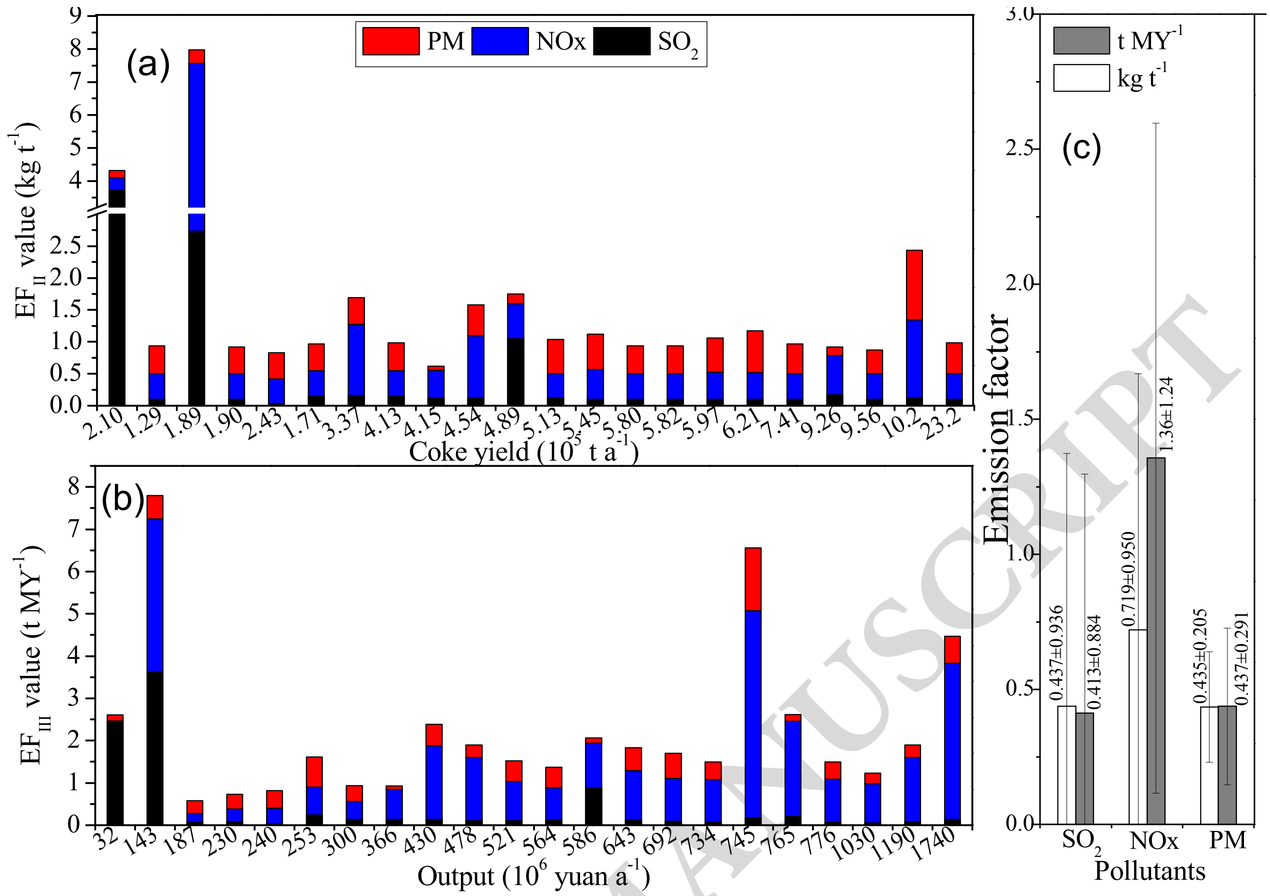

Fig. 4 EF$_{II}$ and EF$_{III}$ values of SO$_2$, NOx, and PM for 22 coke making companies

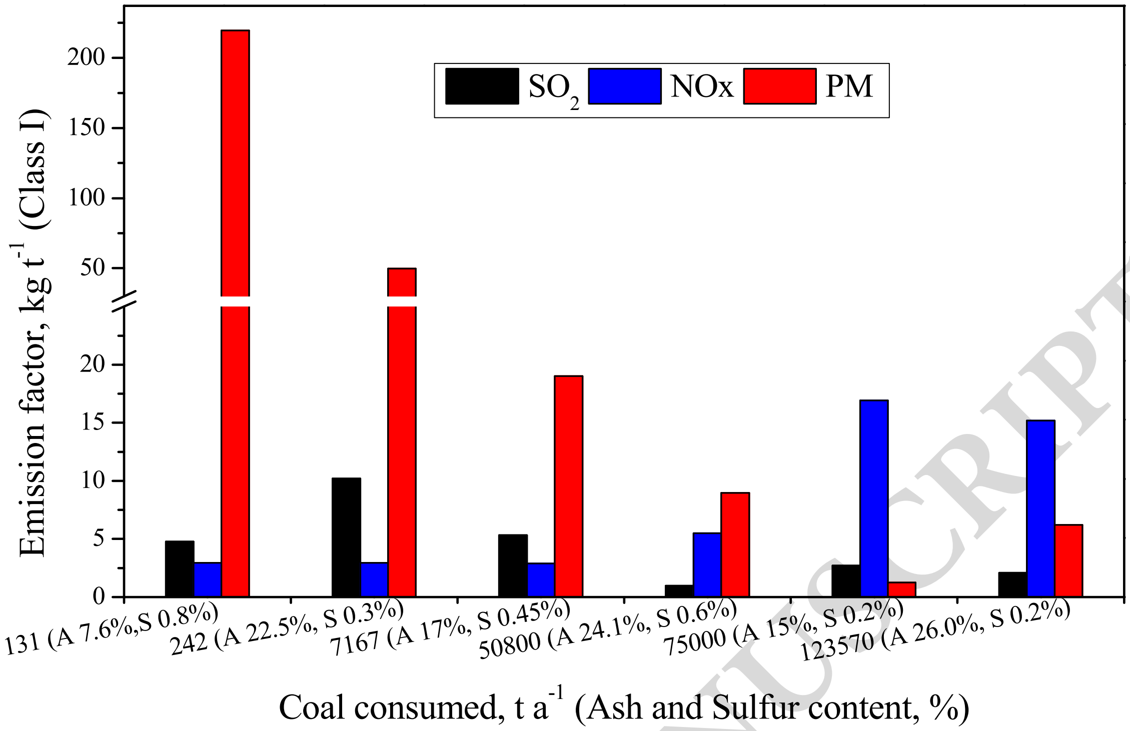

Fig. 5. EF_I values of SO_2, NOx, and PM for 6 cement making companies