*Aerosol and Air Quality Research*, 18: 3115–3126, 2018
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ISSN: 1680-8584 print / 2071-1409 online
doi: 10.4209/aaqr.2018.08.0282

# 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 rapid development in China, small-scale boilers (SCBs) still occupy a prominent place in industry. Due to the lack of pollutant removal devices (RDs), SCBs emit large quantities of pollutants, which merit increased attention. In this study, various SCBs (operating on coal, gangue, coke oven gas, coal gas, and natural gas) used in bathing, heating, power generation, and coke and cement making were investigated for their $SO_2$, $NO_x$, and PM emission factors (EFs). The EFs were expressed as the emitted pollutant mass associated with fuel consumption ($EF_I$), product yield ($EF_{II}$), industrial output ($EF_{III}$), and power generation ($EF_{IV}$). Of 17 civil SCBs, 4, 14, and 10 were not equipped with PM, $NO_x$, and $SO_2$ RDs, respectively. Generally, the $EF_I$ values for all of the SCBs decreased with increasing coal consumption. The averaged $NO_x$ $EF_I$ value for the 3 SCBs with installed $NO_x$ RDs was 2.00 kg $t^{-1}$ versus 3.16 kg $t^{-1}$ for the 17 SCBs. The sulfur content of the coal and the $SO_2$ removal rate were highly influential factors for the $SO_2$ $EF_I$ values. The 4 SCBs without PM RDs possessed an average $EF_I$ value of 23.9 kg $t^{-1}$, which was higher than the corresponding 5.41 kg $t^{-1}$ for the 13 boilers equipped with PM RDs. The $EF_I$, $EF_{II}$, and $EF_{IV}$ values for 9 coal-fired power plants (PPs) exhibited the same trends, decreasing as the capacity of the PPs increased from 6 to 330 MW, although slightly higher EFs were found for 600 MW plants compared to 330 MW plants. The gas-fired PPs possessed higher $NO_x$ EFs than both the coal- and gangue-fired plants, and the gangue-fired PPs displayed significantly higher EFs than coal-fired PPs with the same individual block power capacity. Because flue gas produced in the coking factories was not fully emitted during the combustion process, no correlation existed between the EFs (expressed as $EF_{II}$ and $EF_{III}$) and coke production or industrial output. Moreover, due to the lack of $NO_x$ RDs, the EFs of $NO_x$ were higher than those of $SO_2$ and PM in the coking industry. Among 6 small- and medium-sized cement companies, the factories with lower cement production possessed higher $EF_I$ values for PM. A reverse trend was exhibited by the $NO_x$ $EF_I$, however, with high combustion temperatures at factories with high production being the possible explanation.

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

## 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 has 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,

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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.*, 2017b).

$SO_2$, $NO_x$, 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 controlled due to the high cost (Zhang *et al.*, 2015).

Residential stationary sources including stoves, masonry heaters, and small-scale boilers for heating and bathing are one of the 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-scale coal-fired PPs, few studies were conducted on small-scale gangue- and gas-fired PPs (Li *et al.*, 2016; Dodla *et al.*, 2017; Li *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 the 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-scale enterprises distributed loosely across the 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 (Liu *et al.*, 2009, 2013; Mu *et al.*, 2013; Saikia *et al.*, 2015; Mu *et al.*, 2017). China has the largest cement production in world and accounts for 60% the total world production in 2012 due to its fast urbanization (Chen *et al.*, 2015a). The total coal and electricity consumptions of Chinese cement industry in 2009 were $1.87 \times 10^8$ t and $1.38 \times 10^9$ kWh, resulted in the emission of $8.9 \times 10^5$ t of $SO_2$, $1.69 \times 10^6$ t of $NO_x$, and $3.58 \times 10^6$ 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-scale 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 plants.

## METHODS

In this study, 17 civil small-scale 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 Eqs. (1)–(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 $(10^6 \text{ yuan})^{-1}$ 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:

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

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 $m^{-3}$).

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

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 $a^{-1}$).

$$EF_{III} = \frac{C_i \times V_f \times m_F}{m_P} \quad (3)$$

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 $a^{-1}$).

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

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 Heating, Bathing, and Power***

The needed theoretical air volume for complete combustion of 1 kg of coal or gangue was calculated as follows:

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

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 Eq. (6):

$$V_f^0 = V_{RO_2} + V_{H_2O}^0 + V_{N_2}^0 \quad (6)$$

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 $V_a^0$ ($m^3$ $kg^{-1}$).

$$V_{RO_2} = V_{CO_2} + V_{H2O} + V_{N_2} = 0.01867\omega(C_{ar}) + 0.007\omega(S_{ar}) + 0.0016\omega(N_{ar}) \quad (7)$$

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

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 Eq. (10):

$$V_f = V_f^0 + (\alpha - 1)V_a^0 + 0.0161(\alpha - 1)V_a^0 \quad (10)$$

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 cannot be obtained as aforementioned method and should be calculated by Eq. (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***

The emission amounts of pollutants from the SCBs were higher than those of large-scale coal-fired boilers due to the absence of pollutant RDs (Ma *et al.*, 2017b). Table 1 listed the parameters for 17 civil coal-fired SCBs for heating, bath, and production. The coal consumptions were ranged from 30 to 70,683 t $a^{-1}$ for these 17 companies. The companies with coal consumption less than 1100 t $a^{-1}$ were

**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 $a^{-1}$) | $NO_x$ (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.

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 desulfurization (WFGD) technology was not used in these SCBs. The applied PM RDs in these SCBs contained fabric filters, water bath, and ceramic multi-channel 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 18,250, 42,000, and 70,683 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, 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.

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 desulfurizer. The rest of the 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 and 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

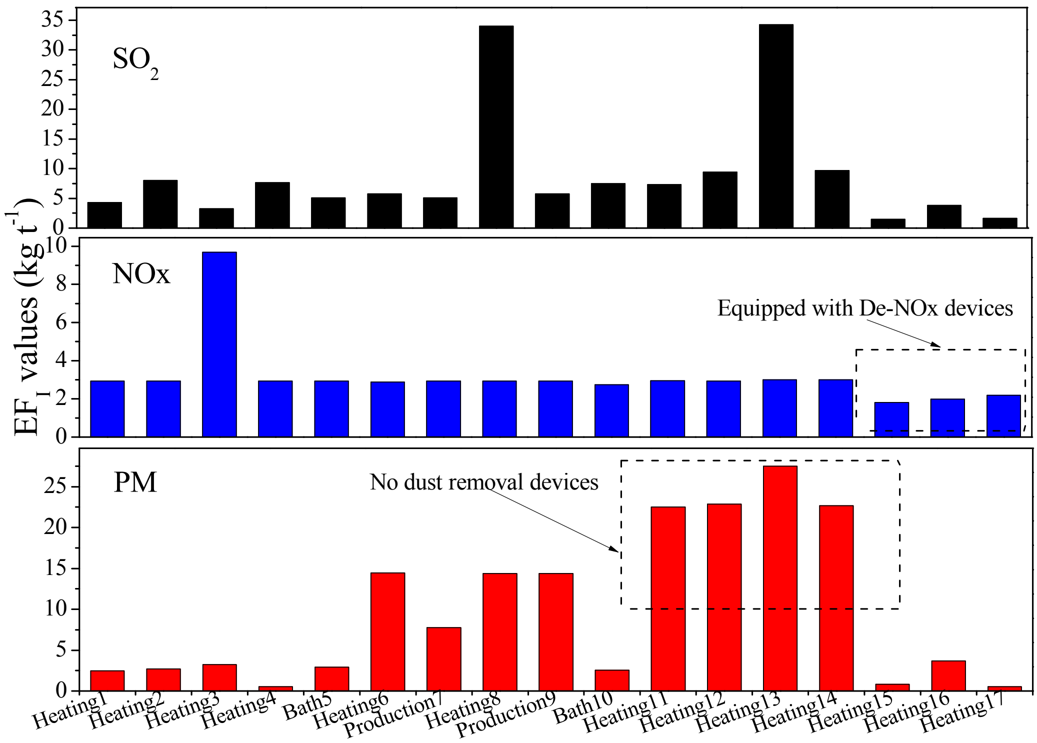


**Fig. 1.** $EF_I$ values for 17 small-scaled boilers for bath, heating, and production industries.

± 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.*, 2017b). The influence of fuel types and individual block power capacity (IBPC) on pollutant EFs should be discussed.

In this study, 15 power plants (PPs)—1 natural gas-fired PP, 1 coke oven gas-fired PP, 2 coal gas-fired PPs with IBPCs of 3 and 6 MW, 2 gangue-fired PPs with IBPCs of 135 and 25 MW, and 9 coal-fired PPs with IBPCs ranging from 6 to 600 MW—were examined. 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 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) for PM. 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 135 MW 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 $EF_I$

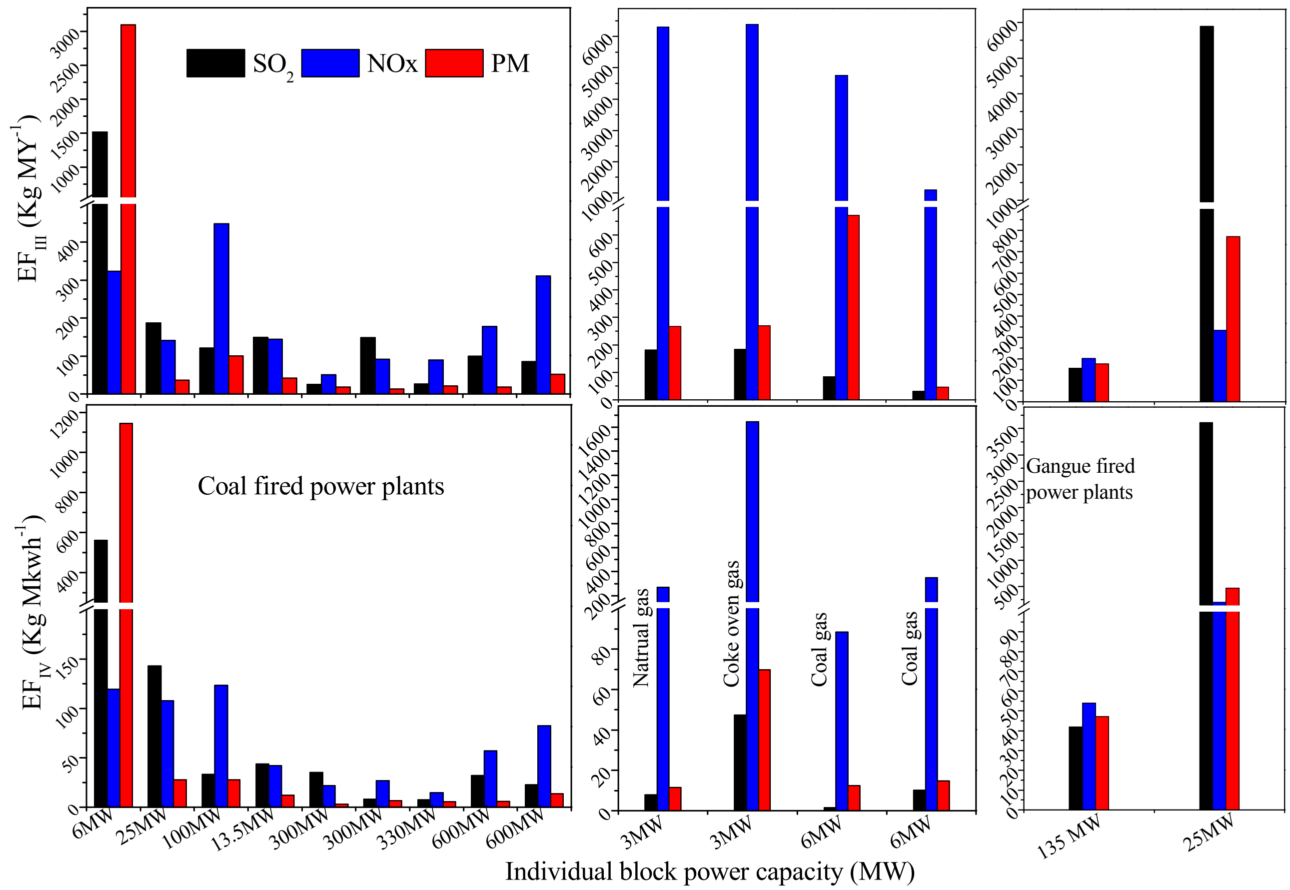


**Fig. 2.** $EF_{III}$ and $EF_{IV}$ of pollutants for 15 PPs based on power capacity and industrial output.

**Table 2.** $EF_I$ values of $SO_2$, $NO_x$, 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 |
| $NO_x$ | 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.

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 > 300–330 MW. 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 significant 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 300 MW 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.* (2017b) also put forward that the pollutant EFs decreased with the increase of IBPC values of PPs. Even without any dust removal devices, the $PM_{2.5}$ EFs could also decrease from 153 g $t^{-1}$ for 100 MW PP to 123 g $t^{-1}$ for 300 MW PP.

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

$$EF_{PM_{2.5}\text{ or }PM_{10}} = EFPM \times \text{mass contribution of } PM_{2.5} \text{ or } PM_{10} \text{ to total PM} \tag{12}$$

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 Eq. (12).

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 at 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.*, 2017b). 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.*, 2017b). The $PM_{2.5}$ EFs for coal- and gangue-fired PPs were far less than those of household coal stoves. Chen *et al.* (2015b) 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.

***Emission of Air Pollutants from Coke Making Industries***

In this study, 22 small- and medium-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 $2.10 \times 10^4$ to $2.31 \times 10^6$ tons.

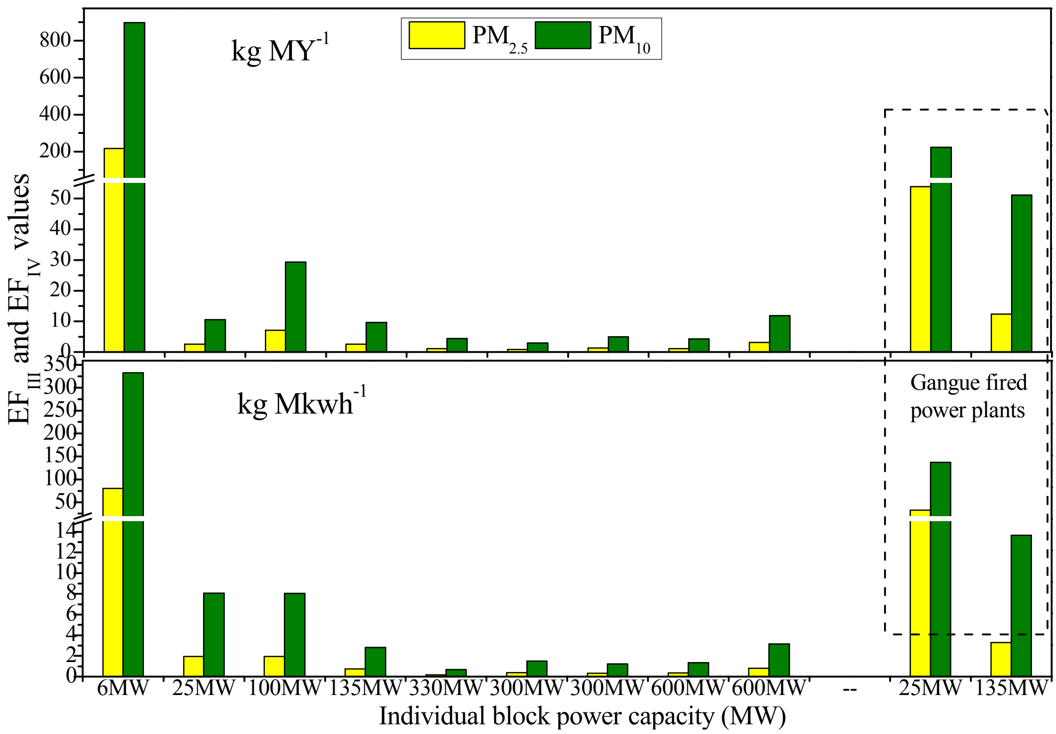


**Fig. 3.** $EF_{III}$ and $EF_{IV}$ values of $PM_{2.5}$ and $PM_{10}$ from coal- and gangue-fired power plants.

**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 |

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 significant fluctuation of the $SO_2$ removal rate (0.00–98.1%) occurred among these factories. The $SO_2$ removal measures contained wet and dry FGD methods, and the desulfurization reagents were NaOH, $Ca(OH)_2$, $NH_3$, and $Na_2CO_3$.

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 determine, so $EF_I$ cannot 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)$^{-1}$.

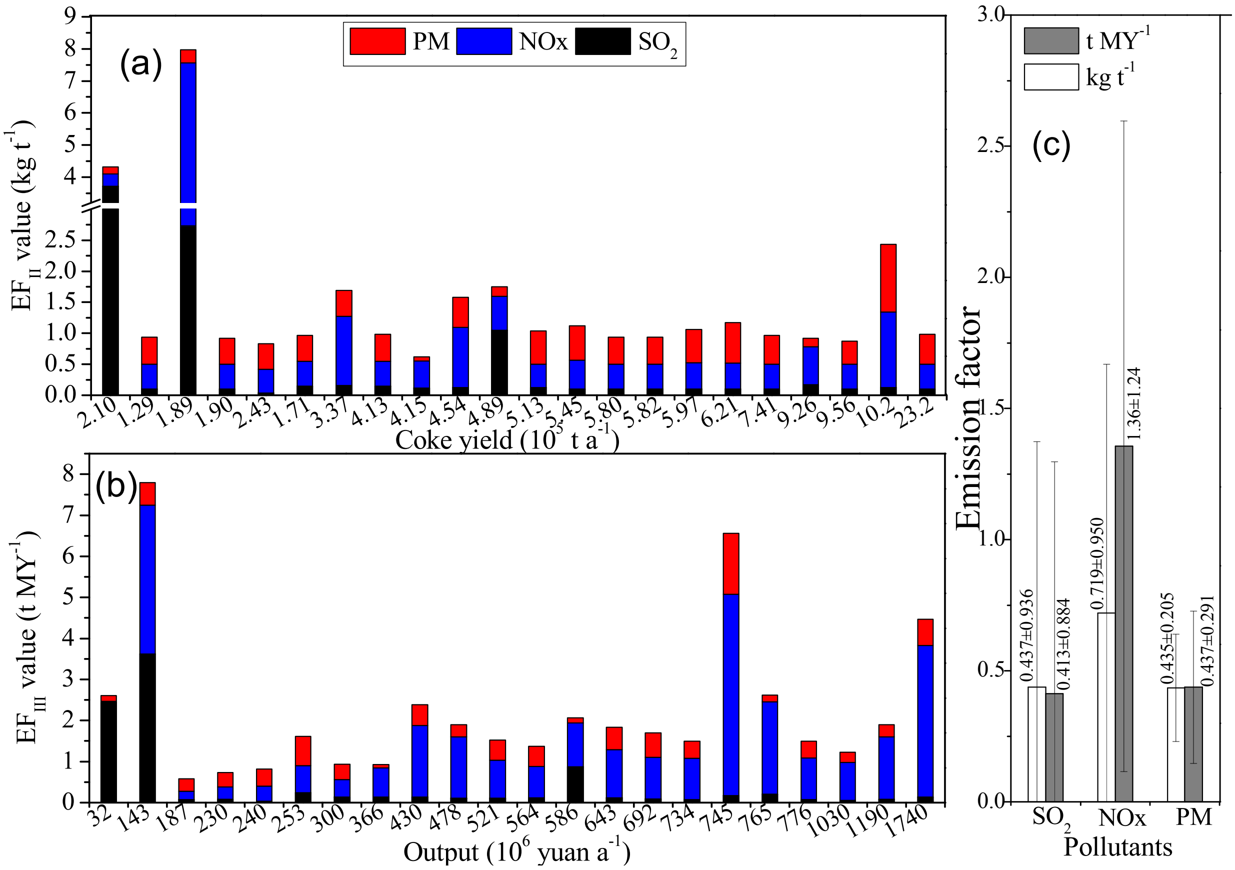


**Fig. 4.** $EF_{II}$ and $EF_{III}$ values of $SO_2$, $NO_x$, and PM for 22 coke making companies.

**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-$NO_x$ (%) | De-PM (%) | De-$SO_2$ (%) | $SO_2$ (t) | $NO_x$ (t) | PM (t) | ¥ Output ($10^9$ yuan) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 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 |

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.* (2015a) 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-scale 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 with $NO_x$ 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 more 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 less 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).

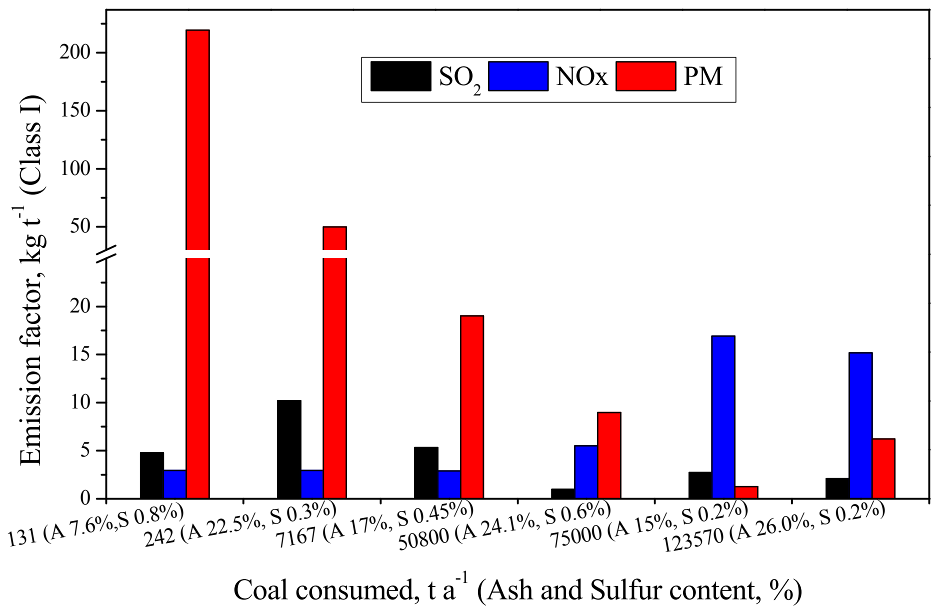


**Fig. 5.** $EF_I$ values of $SO_2$, $NO_x$, and PM for 6 cement making companies.

**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 $(10^4\ yuan)^{-1}$ | | |
|---|---|---|---|---|---|---|---|
| | $SO_2$ | $NO_x$ | PM | | $SO_2$ | $NO_x$ | 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 |

## CONCLUSIONS

In this study, 17 civil SCBs for heating, bathing, and production; 13 coke making companies; 15 power plants (PPs; 9 coal-fired, 2 gangue-fired, 1 coke oven gas-fired, 1 natural gas-fired, and 2 coal gas-fired); 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 in Shanxi Province, China.

1) Of the 17 civil SCBs, 4, 14, and 10 were not equipped with PM, $NO_x$, and $SO_2$ RDs, respectively. Generally, the $SO_2$, $NO_x$, and PM EFs decreased with increasing coal consumption. The 3 SCBs with the highest coal consumption displayed the lowest $EF_I$ values, which 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.

The $NO_x$ $EF_I$ values were lower (1.81–2.19 kg $t^{-1}$; mean ± SD: 2.00 ± 0.192 kg $t^{-1}$) for the 3 factories equipped with $NO_x$ RDs than for the other 14 (2.93–9.68 kg $t^{-1}$; mean ± SD: 3.41 ± 1.79 kg $t^{-1}$). The sulfur content of the coal and the $SO_2$ removal rate were key influential factors for the $SO_2$ $EF_I$. The highest $SO_2$ $EF_I$, 34.3 kg $t^{-1}$, was found at a factory without any installed RDs that was burning coal with 1% sulfur. Higher average PM $EF_I$ values (23.9 ± 2.41 kg $t^{-1}$) were exhibited by the 4 factories without PM RDs compared to the 13 equipped with dust removal devices (5.41 ± 5.44 kg $t^{-1}$).

2) For the coal-, coal gas-, and gangue-fired power plants (PPs), generally, $EF_I$, $EF_{III}$, and $EF_{IV}$ decreased with increasing IBPC. Lacking $SO_2$, $NO_x$, and PM RDs, gas-fired PPs possessed higher $NO_x$ EFs but similar $SO_2$ and PM EFs compared to coal- and gangue-fired plants, and given the same IBPC values, gangue-fired PPs displayed higher $EF_I$, $EF_{III}$, and $EF_{IV}$ values than coal-fired PPs. The $EF_I$, $EF_{III}$, and $EF_{IV}$ values for coal-fired PPs decreased as the IBPC increased, in the order of 6 MW > 25 MW > 100 MW > 135 MW > 300 and 330 MW. The $SO_2$ and PM EFs for 600 MW coal-fired plants, however, were similar to those for 300–330 MW plants, although they exhibited higher $NO_x$ EFs than 135 MW coal-fired plants, due to the use of high combustion temperatures at the 600 MW plants. The $EF_I$, $EF_{III}$, and $EF_{IV}$ values for $PM_{2.5}$ and $PM_{10}$ followed the same trends as those for the overall PM.

3) The $EF_{II}$ and $EF_{III}$ values for 22 coking companies were not correlated with coke production or industrial output, as the flue gas was not fully emitted during the combustion process.

4) Generally, the $SO_2$ $EF_I$ values (0.964–10.2 kg $t^{-1}$) for the cement factories were not correlated with coal consumption or cement output. However, the PM $EF_I$ values were negatively correlated with the aforementioned variables: The factory that consumed the least amount of coal (131 t $a^{-1}$) exhibited the highest PM EF value (220 kg $t^{-1}$), whereas a factory with significantly higher consumption (75,000 t $a^{-1}$) exhibited the lowest value (1.26 kg $t^{-1}$). Additionally, the PM $EF_I$ values for the cement factories were higher than those for the coal-, gangue-, and gas-fired power plants. Factories with high cement output possessed high $NO_x$ EFs as a result of using a high combustion temperature. $EF_{II}$ and $EF_{III}$ values were not correlated with cement production or coal consumption.

## CKNOWLEDGEMENTS

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

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*Received for review, August 13, 2018*
*Revised, September 21, 2018*
*Accepted, October 25, 2018*