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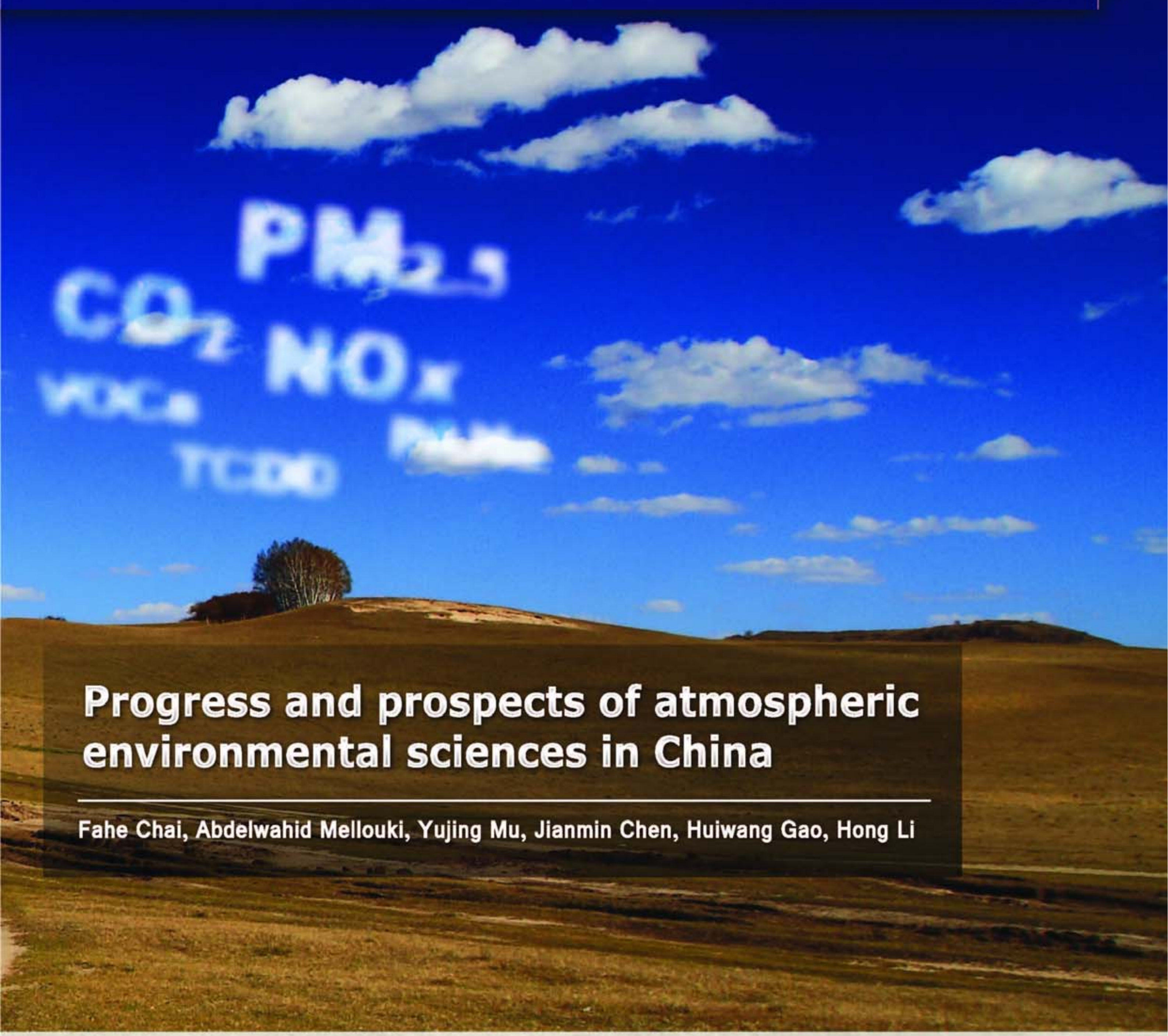

Progress and prospects of atmospheric environmental sciences in China

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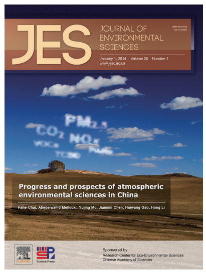

Emission factors of polycyclic aromatic hydrocarbons from domestic coal combustion in China

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ABSTRACT

Domestic coal stove is widely used in China, especially for countryside during heating period of winter, and polycyclic aromatic hydrocarbons (PAHs) are important in flue gas of the stove. By using dilution tunnel system, samples of both gaseous and particulate phases from domestic coal combustion were collected and 18 PAH species were analyzed by GC-MS. The average emission factors of total 18 PAH species was 171.73 mg/kg, ranging from 140.75 to 229.11 mg/kg for bituminous coals, while was 93.98 mg/kg, ranging from 58.48 to 129.47 mg/kg for anthracite coals. PAHs in gaseous phases occupied 95% of the total of PAHs emission of coal combustion. In particulate phase, 3-ring and 4-ring PAHs were the main components, accounting for 80% of the total particulate PAHs. The total toxicity potency evaluated by benzo[*a*]pyrene-equivalent carcinogenic power, sum of 7 carcinogenic PAH components and 2,3,7,8-tetrachlorodibenzodioxin had a similar tendency. And as a result, the toxic potential of bituminous coal was higher than that of anthracite coal. Efficient emission control should be conducted to reduce PAH emissions in order to protect ecosystem and human health.

Introduction

In 2010, 3.12 × 10^9 tons of coal were consumed in China and it was 68% of the primary energy consumption. In the composition of total consumption of energy, household consumption was the second-biggest sector (9.16 × 10^7 tons), just below industry (2.96 × 10^9 tons) (China Statistical Yearbook, 2012). Domestic coal-stove combustion is one popular direct combustion manner, especially for heating and cooking in suburban and rural area of northern China in winter (Chen et al., 2004a, 2004b, 2005; Liu et al., 2009). A significant amount of these combustion takes place indoors without efficient emission control and results in serious indoor and outdoor air pollution (Chen et al., 2006; Zhi et al., 2008). Polycyclic aromatic hydrocarbons (PAHs) are a kind of important compounds mainly emitted from incomplete combustion of fossil fuels, which are toxic and carcinogenic to human health (Douben, 2003; Zhang et al., 2008). In order to accurately assess the contribution of domestic coal combustion to atmospheric pollution and the human health risk, detailed characteristics of PAHs from domestic coal combustion are needed.

Some studies have reported the emission factors (EFs) for some domestic coal under the particular combustion conditions and high uncertainty for domestic coal combustion still exists (Chen et al., 2004a, 2004b, 2005; Xu et al., 2006; Tao et al., 2006; Shen et al., 2010). For example, EFs of total 15 or 17 PAH species ranged from 6.25 to 1434.8 mg/kg (Shen et al., 2010; Liu et al., 2009). Because organic compounds can present in both gaseous and particulate phases and the partitioning between the gaseous and particulate phase is influenced by several factors, such as flue gas resident time, dilution ratio, sampling temperature, the gas/particle concentration, organics' vapor pressure and so on (Baker and Eisenreich, 1990; Tuominen et al., 1988), dilution sampling system is often used to obtain representative samples (Chen et al., 2004a, 2004b, 2005; Geng et al., 2012; Liu et al.,

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2009; Wang et al., 2010). Thereby EFs of PAH usually are dependent on coal category, coal origin, stove type, combustion conditions, dilution technologies and so on.

Coal resource is rich in China and widely distributed. But only a few studies about the emission characteristics of PAHs from domestic coal combustion were reported (Shen et al., 2010; Liu et al., 2009; Chen et al., 2004a, 2005; Xu et al., 2006). Therefore, five kinds of widely used raw coal were selected and burned in a domestic coal-stove to study the emission characteristics of PAHs, in which three kinds of raw coal haven't been studied before (Bituminous coals from Yinchuan and Dongsheng, anthracitic coal from Zhijin). PAHs in both gaseous and particulate phases emitted from domestic coal combustion were measured for the investigation of emission characteristics, including EFs, gas-particulate distribution and the potential toxicity risk.

1 Materials and methods

1.1 Fuel and stove

Five raw coals were selected for the combustion experiment. Bituminous coals were from Yinchuan (YC, Ningxia Province), Datong (DT, Shanxi Province) and Dongsheng (DS, Inner Mongolia), anthracite coals were from Zhijin (ZJ, Guizhou Province) and Jingxi (JX, Beijing). These coals were prepared into 5 to 8 cm diameter pieces before being used. The characteristics of the coals are shown in **Table 1**.

The coal-stove used for the experiment, was purchased from the local market. This type of coal stove is widely used for domestic cooking and heating in China. It has a metallic outer cover and thermal-insulated ceramic liner. The cylindrical inner volume is 0.01 m^3.

1.2 Sampling system

The dilution system has been described in detail elsewhere (Geng et al., 2012; Wang et al., 2010, 2013). Coal combustion flue gas from the stove entered the dilution tunnel through a small stack at the top of the stove. The dilution tunnel consisted of two main parts (made of stainless steel including an orthogonal pipe and a horizontal cylindrical tunnel) and a suction fan. The orthogonal pipe of length 1 m and radius 20 cm was connected to the stove for flue gas introduction and first-step dilution with filtered air. At the end of the orthogonal pipe, a horizontal cylindrical tunnel of length 4 m and radius 40 cm was connected for second-step dilution. At the end of the tunnel, there were several orifices for suction fans and sampling. The flow rate of the suction fan was controlled by Venturic tube and fixed at 5800 L/min. The residence time of flue gas in the dilution tunnel was 5.5 sec. After second-step dilution, the temperature of diluted flue gas was 30°C. The particulate PAHs were collected on quartz fiber filters by a middle-volume particle sampler (Dickel-80, Beijing Geological Instrument-Dickel Cooperation limited, China). The gaseous PAHs were collected on a XAD-4 resin packed in a column with poly urethane foam (PUF) in the two end, which was directly connected under the above filter.

1.3 Sampling procedure

Raw coal samples were ignited in the stove using preweighed charcoal (0.5 kg). To avoid the interference of charcoal combustion, the raw coal sample (1.0 kg for each experiment) was put into the stove until smoking from charcoal combustion stopped. It has been proved that both gaseous and particulate emissions after the smoking period of charcoal combustion were very small and could be neglected (Geng et al., 2012). Sampling started when the raw coal bricks were put into the stove and ended until the combustion finished. This process lasted for one hour. The produced ash did not contain visible unburned fuel residues. The weight of the coals was recorded before and after combustion to obtain the actual weight of coal burned.

Considering the uncertainty of the domestic coal combustion, the sampling of gaseous and particulate PAHs was repeated three times for each coal. Three samples of each

Table 1 Analytical characteristics of the studied coals

		Yinchuan	Dongsheng	Datong	Zhijin	Jingxi
Proximate analysis	Moisture (%)	1.30	7.46	6.98	0.94	3.02
(air dry basis)	Volatile matter (%)	19.74	30.82	32.07	5.76	4.44
	Ash (%)	23.28	6.68	9.50	9.08	26.34
	Fixed carbon (%)	55.68	55.04	51.45	84.22	66.20
	Lower heating value (MJ/kg)	19.51	27.51	26.19	31.23	22.73
Elemental analysis	Carbon (%)	62.68	68.72	64.60	81.86	68.26
(air dry basis)	Hydrogen (%)	2.16	3.76	3.56	2.76	0.79
	Nitrogen (%)	0.62	0.90	0.84	1.04	0.26
	Oxygen (%)	9.60	12.28	14.31	2.08	1.08
	Sulfur (%)	0.36	0.20	0.21	2.24	0.25

kind of coal were combined for PAH analysis.

1.4 Analytical method

PUF and XAD-4 resin were purified respectively by dichloromethane for 24 hr. Quartz fiber filters were baked at 650°C for 2 hr, and stored in a desiccator.

The pretreatment and analysis were conducted by China University of Petroleum (Beijing) (Yu et al., 2008). The filter samples were extracted ultrasonically three times with 150 mL of dichloromethane, and each extraction lasted 30 min. PUF and XAD-4 resin samples were extracted for 48 hr with dichromethane in a Soxhlet apparatus, respectively. Surrogate deuterated PAHs (chrysene-*d12*, acenaphthene-*d10*, naphthalene-*d8*, phenanthrene-*d10*, pyrene-*d12*, Supelco, USA) were added prior to the extraction. The extracts were concentrated on a rotary evaporator and fractionated using silica-alumina column chromatography. The PAH fractions were concentrated using rotary evaporation followed by a gentle stream of nitrogen, and internal standard (hexa-methylbenzene, Supelco, USA) was added for quantification of individual PAHs by GC-MS.

Eighteen kinds of PAHs were analyzed in this study, including 16 US EPA priority PAHs, Benzo[*e*]pyrene and coronene. The basic information is shown in **Table 2**. BaPeq is the index of benzo[*a*]pyrene-equivalent carcinogenic power (Cecinato, 1997). TCDD-IEFs is the index of 2,3,7,8-tetrachlorodibenzo-dioxin induction equivalency factors (Bosveld et al., 2002).

Table 2 Abbreviation of studied PAHs and its toxic factors

Name	Ring	BaPeq	TCDD-IEFs
Naphthalene (NAP)	2	–	–
Acenaphthylene (ACY)	3	–	–
Acenaphthene (ACE)	3	–	–
Fluorene (FLO)	3	–	–
Phenanthrene (PHE)	3	–	–
Anthracene (ANT)	3	–	–
Fluoranthene (FLA)	4	–	0.00000001
Pyrene (PYR)	4	–	–
Benz[*a*]anthracene (BaA)	4	0.06	0.00001
Chrysene (CHR)	4	–	0.0001
Benzo[b]fluoranthene (BbF)	5	0.07	–
Benzo[k]fluoranthene (BkF)	5	0.07	–
Benzo[e]pyrene (BeP)	5	–	–
Benzo[a]pyrene (BaP)	5	1	0.0001
Indeno[1,2,3-cd]pyrene (IcdP)	6	0.08	–
Dibenz[a,h]anthracene (DahA)	5	0.6	0.0001
Benzo[g,h,i]perylene (BghiP)	6	–	0.00000001
Coronene (COR)	7	–	–

–: no data.

Bap_{eq}: index of benzo[*a*] pyrene-equivalent carcinogenic power;

TCDD-IEFs: index of 2,3,7,8-tetrachlorodibenzo-dioxin induction equivalently factor.

2 Results and discussion

2.1 Emission factors

EFs of the identified 18 PAHs in gaseous and particulate phases were calculated on a coal-weight basis and shown in **Table 3** with some data cited from other reports for comparing. For bituminous coals, the EFs of total PAHs varied from 140.75 to 229.11 mg/kg, with average of 171.73 mg/kg, while for anthracite, the EFs of total PAHs varied from 58.49 to 129.47 mg/kg, with average of 93.98 mg/kg. The EFs of total PAHs for bituminous coal was 82.73% higher than that for anthracite. Gaseous and total PAH EFs of DS were 220.53 and 229.11 mg/kg, the highest value among the tested five coals. While, the lowest values of gaseous and total PAH EFs (51.87 and 58.49 mg/kg) were from JX anthracite coal. The EFs of PAHs of bituminous coal reported in literature were also much higher than that of anthracite. Therefore, it will be very helpful for reducing PAH emissions from domestic coal combustion by using anthracite coal instead of bituminous coal.

It should be noted that most gaseous PAH emission factors in this study were higher than other study, especially for bituminous coal. On the one hand, the detail compounds contained in PAHs from different publications were not exactly same. For example, NAP was analyzed in this study while it was not analyzed in others. On the other hand, the residence time of flue gas before being collected was also different. The residence time in this study was 5.5 sec while it was 54 sec and 14 sec in Chen's study (Chen et al., 2005) and 60 sec in Dou's study (Dou et al., 2007). Residence time is very important for the condensation of volatile compounds. As for bituminous coal, much volatile compounds evaporated into air. Shorter residence time led to less condense on particulate phase.

The concentration of BaP ranged from 38.13 μg/m^3 (YC) to 855.10 μg/m^3 (DT) (data not shown). In Beijing, the standard maximum concentration limit of BaP is 0.3 μg/m^3 (DB11/501-2007). The BaP concentration from the emission of studied domestic coal was 126–2849 times higher than the standard value, which indicated the pollution of domestic coal combustion to the atmosphere was serious. Therefore, efficient emission control should be conducted to reduce PAHs emissions, such as domestic coal selection, flue gas treatment and so on.

As shown in **Fig. 1**, good correlation between BaP EFs and the total PAH EFs in particulate phase was observed (R^2 = 0.9925). Therefore, the EF of the total PAHs can be derived from the EF of BaP by multiplying the slope in **Fig. 1**, which can be used to estimate the total PAHs when BaP value is available.

Table 3 Emission factors (EFs) of PAHs emitted from domestic raw coal combustion

Coal	Coal district	EF_{gas} (mg/kg)	EF_{pm} (mg/kg)	EF_{total} (mg/kg)	Reference
Bituminous (YC)	Ningxia, China	138.13	2.62	140.75	This study
Bituminous (DS)	Inner Mongolia, China	220.53	8.58	229.11	This study
Bituminous (DT)	Shanxi, China	130.94	14.41	145.35	This study
Bituminous	Beijing, China	76	249	325	Douhan et al., 2007
Bituminous	China	66	94	160	Chen et al., 2005
Bituminous	China	–	–	373	Shen et al., 2010
Bituminous	Beijing and Shanxi, China	76.4–357.6	248.8–1077.2	325.3–1434.8	Liu et al., 2009
Sub-bituminus	China	28	40	68	Chen et al., 2005
Anthracite (ZJ)	Guizhou, China	126.8	2.67	129.47	This study
Anthracite (JX)	Beijing, China	51.87	6.62	58.49	This study
Anthracite	Hunan, China	0.108	0.009	0.117	Chen et al., 2004
Anthracite	Beijing, China	63	1	64	Douhan et al., 2007
Anthracite	China	–	–	4.78	Shen et al., 2010
Anthracite	Beijing and Shanxi, China	47.2–134.5	1.4–21.3	52.8–155.8	Liu et al., 2009

EF_{gas}, EF_{pm}, EF_{total}: PAH emission factor in gaseous phase, particulate phase and both in gaseous and particulate phase, respectively; –: no data.

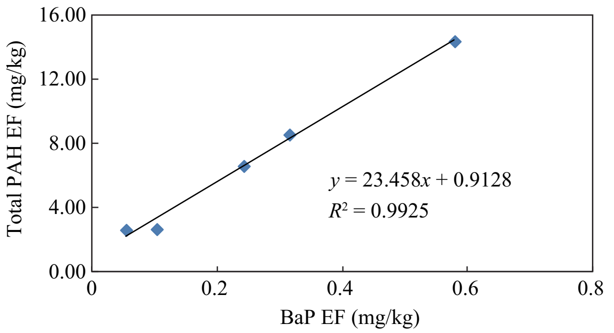

Fig. 1 Correlation of BaP EFs with the total PAH EFs in particulate phases.

2.2 PAH compositions

The mass percent distributions of individual PAHs from bituminous coal combustion was similar to those from anthracite coal combustion, while the mass percent distributions in gaseous phase were greatly different from those in particulate phase (**Fig. 2**). The abundant PAHs in the gaseous phase were those with molecular weight lighter than PHE, while the sum of the other PAHs with heavier mass accounted for less than 10% of the total mass. NAP was the most abundant PAHs in gaseous phase which accounted for 54.54% for bituminous coal and 81.03% for anthracite coal. As for PAHs in particulate phase, the percent of individual PAH was not so concentrated. The mass distribution in particulate phase was dominated by PHE, FLA, PYR, BaA and CHR, in which each species was above 5% and the sum of above PAHs was over 70%. The most abundant PAH in particulate phase was FLA and it accounted for 23.76% for bituminous coal and 21.61% for anthracite coal. For the PAHs other than PHE, FLA, PYR, BaA and CHR, the percentages were mostly from 2% to 5%. The percentage of gaseous PAHs in total were 95% both for bituminous and anthracite coals. That is, the amount of PAHs in gaseous phase dominated the total PAHs emission of domestic coal combustion. The similar result was also reported by other studies. Chen et al. (2004b) found that the ratio of vapor phase to the sum of both phases was 93% for honeycomb coal briquette combustion. When investigated the atmosphere around an oil furnace carbon black manufacturing plant, Tsai et al. (2002) found the gaseous-phase PAHs accounted for 96.3% to 99.7% of the total PAHs.

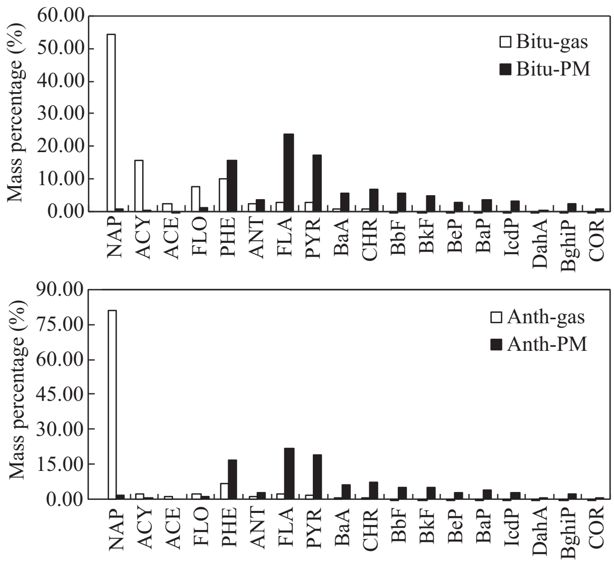

Fig. 2 Mass percentage distribution of PAHs.

Among the detected 18 PAHs, the content of NAP, PHE, FLO, PYR were abundant, which was similar to other studies. Dou et al. (2007) studied the PAH EFs of domestic coal combustion and found that PHE and ACY were abundant, followed by FLO and BbF. Xu et al. (2006) estimated the annual emission of PAHs in China and found the emission of PHE was also plentiful.

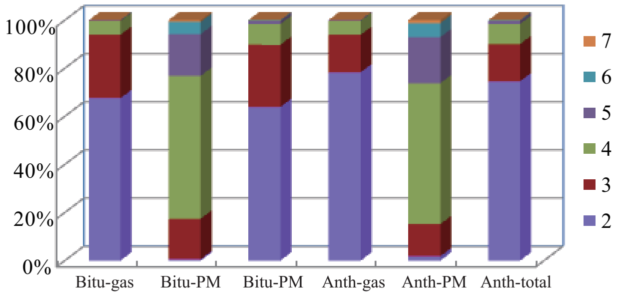

Fig. 3 EFs of PAHs with different rings for flue gas of domestic coal bombustion.

The EFs of PAHs species with different rings both in gaseous and particulate phases are given in **Fig. 3**. Differences between gaseous and particulate phases can be found in both bituminous and anthracite coals. In gaseous phases, PAHs with low rings were the main part of total PAHs, among which the percentage of PAHs with 2-ring were the richest compounds, followed by 3-ring PAHs. Those compounds with 2-ring and 3-ring took up more than 85% of total PAHs in gaseous phase. In particulate phase, the distributions of PAHs with different ring numbers were not uniform. However, in the combustion of both bitunimous and anthracite coals, the average percentage of 4-ring PAHs showed the highest values (57.38% and 56.62%) while the average percentage of 7-ring PAHs was the lowest (0.72% and 0.79%). PAHs in particulate phase with 3-ring and 4-ring were the main components and took up about 80% of total PAHs. Dou et al. (2007) also indicated that 4-ring species were the main part of PAHs in particulate phase emitted from bituminous coals. The total amount of 2-ring and 3-ring PAHs was 90% of the total PAHs, which was similar to the proportion (85%) of 2-ring and 3-ring PAHs in total PAHs for anthracite coal.

2.3 PAH diagnostic ratio

By comparing several PAH diagnostic ratios between sources and receptors, some can be used for source apportionment (Watson, 1984; Yunker et al., 2002; Zhang et al., 2008). In this study, several frequently-used PAHs diagnostic ratios were calculated (**Table 4**). These values were generally comparable to those reported in some other studies for domestic coal combustion (Chen et al., 2004a, 2004b, 2005; Oanh et al., 2005; Yunker et al., 2002; Shen et al., 2010). For gaseous phase, most diagnostic ratios were consistent with each other and the relative standard deviation (RSD) was around or below 20% for the studied five kinds of coals, except BaP/BeP, BaP/(BaP+BeP), BeP/COR, BeP/BghiP. For particulate phase, except FLU/(FLU+PYR), the RSD for all the others PAH ratios were below 50%. For some ratios, the difference was significant between that in gaseous phase and in particulate phase, such as FLU/(FLU+PYR), BaP/COR, PYR/BaP. BaA/BaP, BaP/(BaP+CHR). Thus, the diagnostic ratios in gaseous and in particulate phases need to be investigated separately when these diagnostic ratios are used.

2.4 Potential toxicity risk

To assess the potential toxicity risk to ecosystems and human beings, benzo[*a*]pyrene-equivalent carcinogenic power (BaPE), a sum of 7 carcinogenic PAH components (ΣPAH_7, BaA, CHR, BbF, BkF, BaP, IcdP and DahA) and 2,3,7,8-tetrachlorodibenzodioxin (TCDD)-based total toxicity potency (TEQ) were utilized in many studies (Larsen and Lasen, 1998; Lu et al., 2008; Bhargava, 2004; Liu et al., 2009). The calculated results of potential risk of PAHs emitted from bituminous coals and antracite coals are listed in **Table 5**.

Table 4 PAH diagnostic ratios for five studied domestic coal combustion

	Gaseous phase		Particulate phase	
	Average ± S.D.	RSD (%)	Average ± S.D.	RSD (%)
ANT/(ANT+PHE)	0.17 ± 0.03	18.37	0.14 ± 0.05	36.97
FLU/(FLU+PYR)	0.64 ± 0.12	19.15	0.06 ± 0.03	56.61
BaA/CHR	0.91 ± 0.09	10.21	0.82 ± 0.20	24.43
BbF/BkF	1.19 ± 0.23	19.65	1.04 ± 0.16	15.44
IND/BghiP	1.36 ± 0.07	4.96	1.33 ± 0.10	7.19
IND/(IND+BghiP)	0.58 ± 0.01	2.10	0.57 ± 0.02	3.08
BaP/COR	0.10 ± 0.01	11.31	0.48 ± 0.22	45.95
PYR/BaP	32.81 ± 7.44	22.67	5.84 ± 2.37	40.69
BaA/(BaA+CHR)	0.47 ± 0.02	5.27	0.45 ± 0.06	14.02
BaA/BaP	9.45 ± 1.00	10.57	2.00 ± 0.86	43.05
BaP/(BaP+CHR)	0.09 ± 0.01	10.34	0.31 ± 0.11	36.47
BaP/BeP	1.45± 1.20	82.49	1.32 ± 0.58	44.03
BaP/(BaP+BeP)	0.51 ± 0.22	42.89	0.55 ± 0.12	21.29
BeP/COR	0.13 ± 0.12	93.16	0.36 ± 0.09	25.14
BeP/BghiP	2.77 ± 2.28	82.20	1.30 ± 0.34	26.04

Table 5 Potential toxicity risk of PAHs emitted from domestic coal combustion

	Bituminous			Anthracite		
	Gaseous	Particulate	Total	Gaseous	Particulate	Total
ΣPAH_7	1.644	2.148	4.410	1.177	1.382	2.560
BaPE	0.132	0.333	0.532	0.092	0.235	0.327
TEQ	0.0002	0.0004	0.0007	0.0001	0.0003	0.0004

The results of BaPE, ΣPAH_7 and TEQ exhibited a similar tendency that the potential health risk of bituminous coals was higher than that of anthracite coals. Although PAHs in gaseous phase took up most part of PAH mass, its contribution to the total toxicity was still less than PAH in particulate phase. For each coal, the carcinogenic power was different. The total toxicities of DS and DT were high, which was coincident with the high PAHs EFs.

3 Conclusions

Using dilution system, gaseous and particulate samples from domestic coal combustion were collected to analyze 18 kinds of PAHs. Both of bituminous and anthracite coals showed high EFs and potential toxicity, and the concentration of BaP was 126 to 2849 times higher than the emission standard value of Beijing (DB11/501-2007). Therefore, efficient emission control should be conducted to reduce PAHs emissions, such as domestic coal selection, flue gas treatment and so on. Gaseous PAHs from the domestic coal combustion accounted for the most part of total PAHs emission and the potential toxicity risk of gaseous PAHs was almost comparable to that of particulate PAHs. Previous studies mainly focused on particulate PAHs measurement and would greatly underestimate the impact on atmospheric PAHs. In the future, relevant study should be enhanced to master the comprehensive characteristics of PAHs emissions from domestic coal combustion.

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REFERENCES

Baker J E, Eisenreich S J, 1990. Concentrations and fluxes of polycyclic aromatic hydrocarbons and polychlorinated biphenyls across the air-water interface of Lake Superior. *Environmental Science and Technology*, 24(3): 342–352.

Bhargava A, Khanna R N, Bhargava S K, Kumar S, 2004. Exposure risk to carcinogenic PAHs in indoor-air during biomass combustion whilst cooking in rural India. *Atmospheric Environment*, 38(28): 4761–4767.

Bosveld A T C, de Bie P A, van den Brink N W, Jongepier H, Klomp V A, 2002. *In vito* EROD induction equivalency factors for the 10 PAHs generally monitored in risk assessment studies in the Netherlands. *Chemosphere*, 49(1): 75–83.

Cecinato A, 1997. Polycyclic aromatic hydrocarbons (PAH), benz(*a*) pyrene (BaPY) and nitrated-PAH (NPAH) in suspended particulate matter. *Annali Di Chimica*, 87: 483–496.

Chen Y J, Bi X H, Mai B X, Shen G, Fu J, 2004a. Emission characterization of particulate/gaseous phases and size association for polycyclic aromatic hydrocarbons from residential coal combustion. *Fuel*, 83(7–8): 781–790.

Chen Y J, Bi X H, Mai B Z, Sheng G Y, Fu J M, 2004b. Quantitative study and size distribution of polycyclic aromatic hydrocarbons from honeycomb coal brequette combustion. *Environmental Pollution and Control*, 26(6): 415–423.

Chen Y J, Sheng G Y, Bi X H, Feng Y L, Mai B X, Fu J M, 2005. Emission factors for carbonaceous particles and polycyclic aromatic hydrocarbons from residential coal combustion in China. *Environmental Science and Technology*, 39(6): 1861–1867.

China Statistical Yearbook, 2010, China Statictics Press, Beijing. 2011.

Chen Y J, Zhi G R, Feng Y L, Fu J M, Sheng G Y, Simoneit B R T, 2006. Measurements of emission factors for primary carbonaceous particles from residential raw-coal combustion in China. *Geophysical Research Letter*, 33: L20815. DOI:10.1029/2006GL026966.

Dou H, Chang B, Wei Z C, Qiu W, Liu S Z, Liu Y et al., 2007. Emission factors of PAHs in residential coal combustion in China. *Acta Scientiae Circumstantiae*, 27(11): 1783-1788.

Douben P E T, 2003. PAHs: An Ecotoxicological Perspective. Wiley, New York.

Geng C M, Wang K, Wang W, Chen J H, Liu X Y, Liu H J, 2012. Smog chamber study on the evolution of fume from residential coal combustion. *Journal of Environmental Sciences*, 24(1): 169–176.

Larsen J C, Larsen P B, 1998. Chemical carcinogens. In: Air Pollution and Health (Hester R, Harrison R, eds.). Cambridge, UK: The Royal Society of Chemistry, 33–56.

Liu W X, Dou H, Wei Z C, Chang B, Qiu W X, Liu Y et al., 2009. Emission characteristics of polycyclic aromatic hydrocarbons from combustion of different residential coals in North China. *Science of the Total Environment*, 407(4): 1436–1446.

Lu H, Zhu L Z, Chen S G, 2008. Pollution level, phase distribution and health risk of polycyclic aromatic hydrocarbons in indoor air at public places of Hangzhou, China. *Environmental Pollution*, 152(3): 569–575.

Oanh N T K, Albina D O, Ping L, Wang X K, 2005. Emission of particulate matter and polycyclic aromatic hydrocarbons from select cookstove-fuel systems in Asia. *Biomass and Bioenergy*, 28(6): 579–590.

Shen G, Wang W, Yang Y, Zhu C, Min Y J, Xue M et al., 2010. Emission factors and particulate matter size distribution of polycyclic aromatic hydrocarbons from residential coal combustions in rural Northern China. *Atmospheric Environment*, 44(39): 5237-5243.

Tao S, Li X R, Yang Y, Coveney R M, Lu X X, Chen H T et al., 2006. Dispersion modeling of polycyclic aromatic hydrocarbons from combustion of biomass and fossil fuels and production of coke in Tianjin, China. *Environmental Science and Technology*, 40(15): 4586–4591.

Tsai P J, Shieh H Y, Lee W J, Lai S O, 2002. Characterization of PAHs in the atmosphere of carbon black manufacturing workplaces. *Journal of Hazardous Materials*, 91(1-3): 25–42.

Tuominen J, Salomaa S, Pyysalo H, Skytta E, Tikkanen L, Nurmela T et al., 1988. Polynuclear aromatic compounds and genotoxicity in particulate and vapor phases of ambient air: effect of traffic, season, and meteorological conditions. *Environmental Science and Technology*, 22(10): 1228–1234.

Wang K, Geng C M, Wang W, Liu X Y, Liu H J, Ge M F, 2010. Characterization of residential coal combustion: products and in situ photo-oxidation. Heterogeneous Combustion, Nova Science Publishers, 2010, ISBN: 978-1-61761-324-1 USA.

Wang Q, Geng C M, Lu S H, Chen W T, Shao M, 2013. Emission factors of gaseous carbonaceous species from residential combustion of coal and crop residue brequettes. *Frontiers of Environmental Science and Engineering*, 7(1): 66–76.

Watson J G, 1984. Overview of receptor model principles. *Journal of the Air Pollution Control Association*, 34: 619–623.

Xu S S, Liu W X, Tao S, 2006. Emission of polycyclic aromatic hydrocarbons in China. *Environmental Science and Technology*, 40(3): 702–708.

Yu G G, Wang T G, Zhu X L, Wu D P, 2008. Source appointment of PAHs in aerosol of northwest of Beijing. *Environmental Chemistry*, 27(2): 245–250.

Yunker M B, Macdonald R W, Vingarzan R, Mitchell H R, Goyette D, Sylvestre S, 2002. PAHs in the Fraser River basin: a critical appraisal PAH ratios as indicators of PAH source and composition. *Organic Geochemistry*, 33(4): 489–515.

Zhang Y X, Schauer J J, Zhang Y H, Zeng L M, Wei Y J, Liu Y et al., 2008. Characteristics of particulate carbon emissions from real-world Chinese coal combustion. *Environmental Science and Technology*, 42(14): 5068–5073.

Zhi G R, Chen Y J, Feng Y L, Xiong S C, Li J, Zhang G et al., 2008. Emission characteristics of carbonaceous particles from various residential coal-stoves in China. *Environmental Sciences and Technology*, 42(9): 3310–3315.

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