Aerosol and Air Quality Research, 18: 994–1007, 2018

ISSN: 1680-8584 print / 2071-1409 online
doi: 10.4209/aaqr.2018.02.0040

Atmospheric $PM_{2.5}$ and Total PCDD/Fs-WHO_{2005}-TEQ Level: A Case of Handan and Kaifeng Cities, China

Rong Zhao[1], Kangping Cui[1*], Weiwei Wang[1], Lin-Chi Wang[2], Ping Yan[1***]**

[1] *School of Resources and Environmental Engineering, Hefei University of Technology, Hefei 246011, China*
[2] *Department of Civil Engineering and Geomatics, Cheng Shiu University, Kaohsiung 83347, Taiwan*

ABSTRACT

From 2015 to 2017, the atmospheric $PM_{2.5}$, the total PCDD/Fs-WHO_{2005}-TEQ concentrations, $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ contents, and the gas-particle partitioning of PCDD/Fs in Handan and Kaifeng were investigated. In addition, a regression analysis of the air quality index (AQI) and total PCDD/Fs-WHO_{2005}-TEQ concentration was also studied. From 2015–2017, in Handan, the three-year average $PM_{2.5}$ concentrations in spring, summer, autumn and winter were 66.9, 61.3, 74.8, and 138 µg m^{-3}, respectively and averaged 85.3 µg m^{-3}, which was 1.2 orders of magnitude higher than that in Kaifeng (71.1 µg m^{-3}). The three-year average $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ content in spring, summer, autumn, and winter in Handan were 0.88, 0.28, 0.67, and 0.72 ng WHO_{2005}-TEQ g^{-1}, respectively, and averaged 0.64 ng WHO_{2005}-TEQ g^{-1}, which was 1.1 order of magnitude higher than that in Kaifeng (0.57 ng WHO_{2005}-TEQ g^{-1}). The three-year average fraction of gas phase total PCDD/Fs-WHO_{2005}-TEQ concentrations in spring, summer, autumn, and winter in Handan were 26.4%, 62.8%, 28.9%, and 3.34%, respectively, and averaged 30.4%. The three-year average fraction of gas phase total PCDD/Fs-WHO_{2005}-TEQ concentrations in Kaifeng (34.3%) was 1.1 order of magnitude higher than that in Handan (30.4%). Positive correlations between the AQI and the total PCDD/Fs-WHO_{2005}-TEQ concentration were found and their R^2 values in 2015, 2016, and 2017 were 0.929, 0.921, and 0.876, respectively. Therefore, the AQI can be used to roughly predict the level of total PCDD/Fs-WHO_{2005}-TEQ in ambient air through the use of a regression equation in these two cities.

Keywords: AQI; $PM_{2.5}$; PM_{10}; PCDD/Fs; Phase distribution; Regression analysis; TEQ.

INTRODUCTION

Atmospheric particulate matter (PM) is the general various solid and liquid particulate matter present in the atmosphere. A variety of particulate matter disperses in the air to form a relatively large, stable suspension system, the aerosol system; therefore, atmospheric particles are part of the atmospheric aerosol (Ghosh *et al.*, 2014). According to the aerodynamic diameters of PM, it can be divided into TSP (ranging from ~0 to 100 µm), PM_{10} (ranging from ~0 to 10 µm) and $PM_{2.5}$ (ranging from ~0 to 2.5 µm) (Chow *et al.*, 2015; Lu *et al.*, 2016). $PM_{2.5}$ lasts a long time in ambient air and has a significant impact on human health and atmospheric visibility. Some of the particles come directly from natural sources, such as forest fires, volcanic eruptions, and marine spraying, while anthropogenic sources of $PM_{2.5}$ are primarily from petrochemical fuel combustion, biomass burning, waste incineration, automobiles, factories, construction activities, and open burning of non-natural materials.

Primary PM were emitted into the atmosphere directly from emission sources, while the secondary aerosol was formed from precursors, such as sulfur oxides, nitrogen oxides, volatile organic compounds and ammonia, under specific environmental conditions (Lee *et al.*, 2016; Zhu *et al.*, 2017). The chemical and physical composition of PM varies significantly with the locations, climates, and seasons of the year. $PM_{2.5}$ is also known as an inhaled lung particle. Because of its large specific surface area, $PM_{2.5}$ easily enriches a large number of poisonous, harmful substances, stays in the atmosphere longer, and has a longer distance transportation, resulting in greater impact on human health and the atmospheric environment. The WHO set the average $PM_{2.5}$ annual limit at 10 µg m^{-3}, increasing by 4% for every 10 µg m^{-3} of human mortality. $PM_{2.5}$ can be inhaled to

* Corresponding author.
Tel.: +86-186-5595-3355
E-mail address: cuikangping@163.com
** Corresponding author.
Tel.: +886-7-7351275
E-mail address: lcwang@csu.edu.tw
** Corresponding author.
Tel.: +86-188-0551-2007
E-mail address: y9621227@126.com

cause pneumonia and dissolve into the blood and cause diseases of the heart and reproductive system (Yang *et al.*, 2017). Greater amounts of $PM_{2.5}$ in the atmosphere can also significantly reduce atmospheric visibility.

The Air Quality Index (AQI) is based on the ambient air quality standards and pollutants that impact human health, ecology, and the environment, and make the routine monitoring of six air pollutants ($PM_{2.5}$, PM_{10}, SO_2, NO_2, O_3, and CO) concentrations simplified into the form of a single conceptual index value. It classifies air pollution levels and air quality conditions as suitable for representing a city's daily air quality conditions and trends. The AQI can be divided into six levels as follows: 0–50 (Good; Green Color), 51–100 (Moderate; Yellow), 101–150 (Unhealthy for Sensitive Groups; Orange), 151–200 (Unhealthy; Red), 201–300 (Very Unhealthy; Purple) and 301–500 (Hazardous; Maroon), corresponding to the six levels of air quality, the higher the AQI value, the greater the level of air pollution and the more obvious the impact on the human health. Fig. 1 shows the AQI and the corresponding color.

Polychlorinated dibenzo-*p*-dioxins and polychlorinated dibenzofurans (PCDD/Fs) were included in the Stockholm Convention on Persistent Organic Pollutants in 2001, and was one of the first 12 persistent organic pollutants (POPs) to be controlled. The atmosphere is the main way for PCDD/Fs to migrate and transport in the environment, which is also the main way for pollution to reach land and aquatic ecosystems. Because PCDD/Fs can diffuse rapidly in the atmospheric environment, can migrate through the atmosphere to regional units, even globally, and can be exchanged through the atmosphere, water, soil and plants into the human food chain, regional monitoring of the atmospheric environment for PCDD/F pollution and investigation into its environmental impact are very important (Fiedler *et al.*, 1992; Hutzinger *et al.*, 1992). PCDD/Fs are semi-volatile organic compounds (SVOCs) and POPs that are toxic to human health and to the ecosystem (Schecter *et al.*, 2006; Cheruiyot *et al.*, 2015, 2016; Li *et al.*, 2016; Redfern *et al.*, 2017). There are 210 possible congeners of PCDD/Fs, of which only 17 with chlorine atoms attached to the 2, 3, 7, and 8 positions have been shown to be especially toxic. In particular, the 2,3,7,8-tetrachloro-dibenzo-*p*-dioxin (2,3,7,8-TCDD) is one of the most toxic chemicals (Van den Berg *et al.*, 1998; Li *et al.*, 2016). It is more than 1,000 times more toxic than potassium cyanide, which is known as the "century poison" (Li *et al.*, 2008). The International Cancer Center has classified it as a human carcinogen (IARC, 1997; U.S. Department of Health and Human Services, 2000; Paustenbach, 2002; Cole *et al.*, 2003). A large number of studies have shown that very low concentrations of PCDD/Fs can cause lethal effects in animals and can also lead immune toxicity, reproductive disorders, and endocrine function changes, the most serious irreversible teratogenic, carcinogenic, mutagenic effect (Zhou *et al.*, 2002). There is given a toxicity equivalence factor (TEF) of 1, and the other 16 congeners have TEF values set relative to this. Furthermore, these TEFs are multiplied by the corresponding concentrations of individual homologues, when then produce the toxic equivalent quantities (TEQs) (Lohmann and Jones, 1998; Van den Berg *et al.*, 1998; Cheruiyot *et al.*, 2016). Since PCDD/Fs are SVOCs, their distribution in the atmosphere between the gas-phase and the particle-phase determines their subsequent fate (Lohmann *et al.*, 2000; Suryani *et al.*, 2015). PCDD/Fs can be removed from ambient air by both dry and wet deposition (Huang *et al.*, 2011; Mi *et al.*, 2012; Redfern *et al.*, 2017).

Two industrial cities in China, Handan City and Kaifeng City, were investigated in this study. Their $PM_{2.5}$ data from 2015 to 2017 were obtained from the Environmental Monitoring Website. The total PCDD/Fs-WHO_{2005}-TEQ ambient concentrations were estimated using the equations reported in previous study, which demonstrate the relationship between PM_{10} values and total PCDD/F concentrations. Then the gas-particle phase distribution formula was used to calculate $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ content.

AQI	Levels of Health Concern	Color
0 to 50	Good	Green
51 to 100	Moderate	Yellow
101 to 150	Unhealthy for Sensitive Groups	Orange
151 to 200	Unhealthy	Red
201 to 300	Very Unhealthy	Purple
301 to 500	Hazardous	Maroon

Fig. 1. Six levels of AQI, the corresponding color and health cercen (https://www.airnow.gov/).

A linear regression analysis of AQI for total PCDD/Fs-WHO_{2005}-TEQ in ambient air was also conducted.

METHODS

The Investigated Cities

Handan is the third largest city in Hebei Province, which is the economic center of the southern province of China. Handan is an industrial city with pillar industries for steel, coal and cement, all of which are high energy consumption and high air pollutant emission industries. Handan is located at the junction of Shanxi, Henan, Shandong, and Hebei provinces, which can be called the industrial center of the four provinces. It is also the hardest hit areas in terms of particulate matter (Ren *et al*., 2004; Wang *et al.*, 2012; Zhao Xiujuan *et al.*, 2012). Handan is located in the western foothills of the Taihang Mountains, east of the North China Plain, and is under the influence of the southwest wind. It is vulnerable to impacts from the Yellow River valley pollution emanating from Shanxi Province (Chen *et al*., 2008). Zhang *et al*. (2012) used online monitoring data of four months to analyze the atmospheric particulate pollution in Handan in the summer and autumn. Wei *et al*. (2014) used online monitoring data to study the characteristics of severe haze pollution in Handan City in January 2013. In recent years, there has been very little research data available for Handan.

Kaifeng City is a key city designated by the state environmental protection administration to prevent and control national air pollution because a significant amount of industrial waste gas and automobile exhaust have caused air pollution in this city. The main air pollution sources include climate and human causes of sand dust, construction dust, coal-based pollution, motor vehicle exhaust pollution, and cooking fume pollution. With the acceleration of the industrialization process and the rapid development of the tertiary industry, in recent years, the number of newly built, reconstructed, and expanded coal-fired boilers in urban areas has expanded to a total of 222, together with 386 originals, totaling 608. These boilers burn 2 million tons of coal each year, generating 430,000 tons of slag, releasing 18,000 tons of soot and 15,000 tons of sulfur dioxide into the atmosphere. Coal has become a major factor causing this area to exceed the limits for major pollutants such as sulfur dioxide and respirable particulate pollution, nearly half of the air pollution load.

Data Collection

The concentrations of $PM_{2.5}$ and PM_{10} in Handan and Kaifeng were obtained from the Environmental Monitoring Station. Both ambient air temperature and rainfall intensity in Handan and Kaifeng were obtained from the Weather Network.

Wang *et al*. (2016) evaluated the concentrations of the 17 PCDD/Fs congeners by using their individual proportions in the total PCDD/F mass concentration, which was deduced from the atmospheric concentration of PCDD/Fs during all four seasons in commercial areas in Taiwan. The total PCDD/F concentration was the average of the results of two analytical equations. One was presented by Huang *et al.* (2011), shown as $y_1 = 0.0472 + 0.0138x$, and the other was presented by Lee *et al.* (2016), shown as $y_2 = 0.0117x - 0.021$, where y_1 and y_2 comprised total dioxin mass concentrations, and x was the concentration of PM_{10} in the atmosphere. The differences between these two regression equations ranged between 20% and 30%, which was acceptable for PCDD/Fs which were in trace amount.

Gas-Particle Partitioning

Gaseous and particulate concentrations of PCDD/Fs, respectively, were evaluated using gas-particle partitioning multiplying the total concentrations of PCDD/Fs. The gas-particle partitioning was simulated with an equation proposed by several researchers that successfully describes the gas-particle partitioning constant (Yamasaki *et al*., 1982; Pankow, 1987; Pankow and Bidleman, 1991, 1992):

$$K_p = \frac{F/TSP}{A} \tag{1}$$

K_p: temperature-dependent partitioning constant ($m^3\ \mu g^{-1}$)
TSP: concentration of total suspended particulate matter, multiplied by PM_{10} concentration with 1.24 ($\mu g\ m^{-3}$)
F: concentration of the compounds of interest bound to particles ($pg\ m^{-3}$)
A: gaseous concentration of the compound of interest ($pg\ m^{-3}$)

Plotting $\log K_p$ against the logarithm of the subcooled liquid vapor pressure, P_L^0, gives

$$\log K_p = m_r \times \log P_L^0 + b_r \tag{2}$$

P_L^0: subcooled liquid vapor pressure (Pa);
m_r: cited slope;
b_r: cited y-intercept.

Complete datasets on the gas-particle partitioning of PCDD/Fs in Taiwan has been reported

(Chao *et al*., 2004), with the values $m_r = -1.29$ and $b_r = -7.2$ with $R^2 = 0.94$. These values were used in this study to establish the partitioning constant (K_p) of PCDD/Fs.

A previous study correlated the P_L^0 of PCDD/Fs with gas chromatographic retention indexes (GC-RI) on a nonpolar (DB-5) GC-column using p,p′-DDT as a reference standard. The correlation has been redeveloped as the following (Hung *et al*., 2002)

$$\log P_L^0 = \frac{-1.34(RI)}{T} + 1.67\times10^{-3}(RI) - \frac{1320}{T} + 8.087 \tag{3}$$

RI: gas chromatographic retention indexes developed by Donnelly *et al*. (1987) and Hale *et al*. (1985).

RESULTS AND DISCUSSION

$PM_{2.5}$ Concentrations

The monthly average $PM_{2.5}$ concentrations in the ambient air of Handan and Kaifeng during the years 2015 and 2017 are shown in Figs. 2(a), 2(b) and 2(c), respectively. In the case of Handan, in 2015, the monthly average $PM_{2.5}$ concentrations ranged between 58.3 and 176 µg m^{-3} , with an average of 90.6 µg m^{-3}, which was a 14.5% order of magnitude lower than for Baoding City (106 µg m^{-3}) (Xing *et al.*, 2017); during 2016, the concentrations ranged from 40.2 to 226 µg m^{-3} and averaged 79.8 µg m^{-3} , which was a 19.0% order of magnitude lower than for Shijiazhuang City (98.5 µg m^{-3}) (Xing *et al.*, 2017); in 2017, the $PM_{2.5}$ concentration ranged from 60.2 to 173 µg m^{-3} at an average of 82.5 µg m^{-3}. During the three years under investigation (2015–2017), the highest monthly average value occurred in December (173 µg m^{-3}), and the lowest $PM_{2.5}$ concentration was in August (58.3 µg m^{-3}). As to seasonal variations, the four seasons were defined as spring (March, April, and May), summer (June, July, and August), autumn (September, October, and November) and winter (January, February and December). From 2015 to 2017, in Handan, the three-year average $PM_{2.5}$ concentrations in spring, summer, autumn, and winter were 66.9, 61.3, 74.8 and 138 µg m^{-3}, respectively. As a whole, the three-year average $PM_{2.5}$ concentration in Handan in winter (138 µg m^{-3}) was 2.3 times that in summer (61.3 µg m^{-3}).

As for Kaifeng, during 2015, the monthly average $PM_{2.5}$ concentrations ranged from 44.0 to 138 µg m^{-3} and averaged 73.8 µg m^{-3}, which was a 23.2% order of magnitude lower than for Zhengzhou City (96.1 µg m^{-3}) (Xing *et al.*, 2017); during 2016, these concentrations ranged from 35.1 to 141 µg m^{-3} and averaged 71.3 µg m^{-3} , which was a 9.2% order of magnitude lower than for Zhengzhou City (78.5 µg m^{-3}) (Xing *et al.*, 2017); in 2017, the monthly average $PM_{2.5}$ concentration ranged from 34.0 to 135 µg m^{-3} with an average of 65.9 µg m^{-3}. During the three years under investigation (2015–2017), the highest monthly average value occurred in January (135 µg m^{-3}), and the lowest $PM_{2.5}$ concentration was in August (38.6 µg m^{-3}). As to seasonal variations, in Kaifeng, from 2015–2017, the three-year average $PM_{2.5}$ concentrations in spring, summer, autumn, and winter were 62.6, 41.3, 64.3 and 116 µg m^{-3}, respectively. Overall, the three-year average of $PM_{2.5}$ concentration in Kaifeng in winter (116 µg m^{-3}) was 2.8 times that in summer (41.3 µg m^{-3}).

Compared to the annual average concentrations of $PM_{2.5}$ in Handan, from 2015 (90.6 µg m^{-3}) to 2016 (79.8 µg m^{-3}), the $PM_{2.5}$ concentration decreased by 11.9%, while, that from 2016 (79.8µg m^{-3}) to 2017 (82.5 µg m^{-3}) increased by 7.0%. In Kaifeng, between 2015 (73.8 µg m^{-3}) and 2016 (71.3 µg m^{-3}), the $PM_{2.5}$ concentration decreased by 3.4%, while that from 2016 (71.3 µg m^{-3}) to 2017 (65.9 µg m^{-3}) the $PM_{2.5}$ value decreased by 7.6%.

Figs. 2(d) and 2(e) show the monthly increase/decrease of the $PM_{2.5}$ concentration in Handan and Kaifeng, respectively. For Handan, from 2015 to 2016, most of the monthly average $PM_{2.5}$ concentrations decreased, which were 27%, 34%, 10%, 34%, 35%, 29%, 45%, 3%, and 19% for January, February, March, May, June, July, August, September, and October, respectively, while those in April, November, and December increased by 7%, 18%, and 28%, respectively. From 2016 to 2017, the decreases of the $PM_{2.5}$ concentration were 36%, 3%, 16%, and 48% for March, April, November, and December, respectively, while those for January, February, May, June, July, August, September, and October increased by 59%, 47%, 61%, 45%, 11%, 55%, 32%, and 63% respectively. As to the seasonal changes of $PM_{2.5}$ concentration, from 2015 to 2016, $PM_{2.5}$ concentrations in spring, summer, and winter decreased by 11%, 36%, and 6% respectively, while that for autumn increased by 0.9%; from 2016 to 2017, both spring and winter levels decreased by approximately 2%, while those in summer and autumn increased by 34% and 15%, respectively.

In Kaifeng, from 2015 to 2016, the monthly average $PM_{2.5}$ concentrations decreased by 14%, 40%, 28%, 17%, 20%, and 33% for February, May, June, July, August, and October, respectively, while those in January, March, April, September, November, and December increased by 9%, 16%, 42%, 12%, 10% and 1%, respectively. From 2016 to 2017, decreased $PM_{2.5}$ concentrations were 4%, 31%, 11%, 18%, 18%, and 34% for January, April, July, September, November and December, respectively, while those for February, May, June, August, and October increased by 44%, 45%, 15%, 6%, and 27%, respectively. From 2015 to 2016, the increases in the seasonal average $PM_{2.5}$ concentrations in spring and winter were 3% and 0.3%, respectively, while the seasonal average $PM_{2.5}$ concentrations in summer and autumn decreased by 22% and 2%, respectively; from 2016 to 2017, those in summer increased by 4%, while those in spring, autumn, and winter decreased by 3%, 9% and 6%, respectively.

In 2017, the annual average $PM_{2.5}$ concentration in Handan (82.5 µg m^{-3}) and Kaifeng (65.9 µg m^{-3}) were 8.3 and 6.6 orders of magnitude higher than the WHO air quality regulated standard (10 µg m^{-3}). With the quick development of the economy and the rapid growth of industrialization, the air quality in China is becoming an increasingly important public issue. A more effective control strategy for reducing the $PM_{2.5}$ concentrations in the ambient air is really very urgent.

According to the above results, it is clear that the ambient air in Handan is more polluted by $PM_{2.5}$ than that in Kaifeng City. This is due to the fact that Handan is a highly industrialized city with large numbers of steel mills and coal-fired power plants, which generated a significant amount of air pollutants.

The monthly average $PM_{2.5}$ concentration is always highest in winter and lowest in summer. This is because the low ground temperature in winter enhances the stability of the atmospher and thus hinders pollutant diffusion and reduces vertical dispersion in the atmosphere (Tang *et al.*, 2017; Xing *et al*, 2017). In addition, in the winter cold season, more demand for heating and larger amounts of coal and biomass combustion produce a significant amount of $PM_{2.5}$ and other pollutants. In the summer, in both Handan and Kaifeng, because of their warm temperate semi-humid semi-arid continental monsoon climate, which makes it hot and rainy in the summer, atmospheric instability is good for vertical dispersion and benefits the proliferation of the atmospheric wet deposition necessary to remove large amounts of $PM_{2.5}$ particles from the air and reduce $PM_{2.5}$ concentrations.

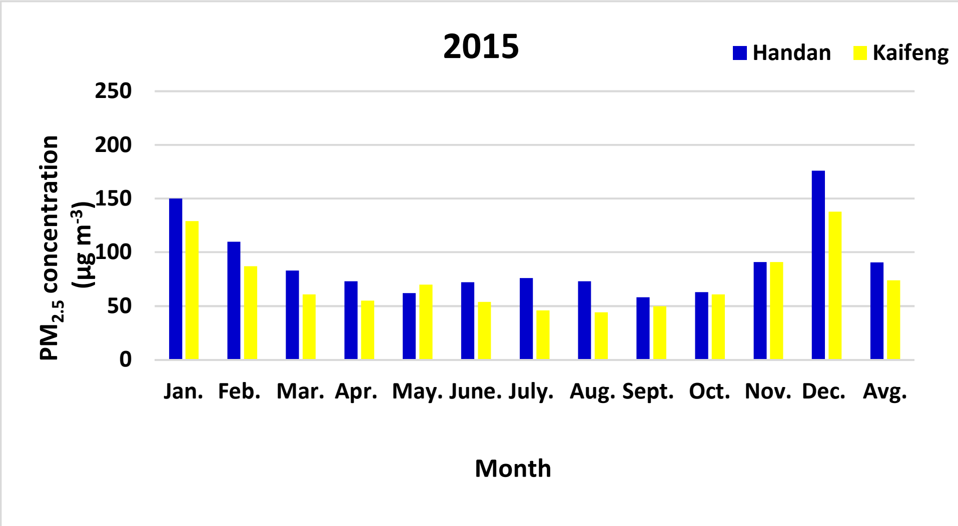

Fig. 2(a). Monthly average atmospheric $PM_{2.5}$ concentration in Handan and Kaifeng during 2015.

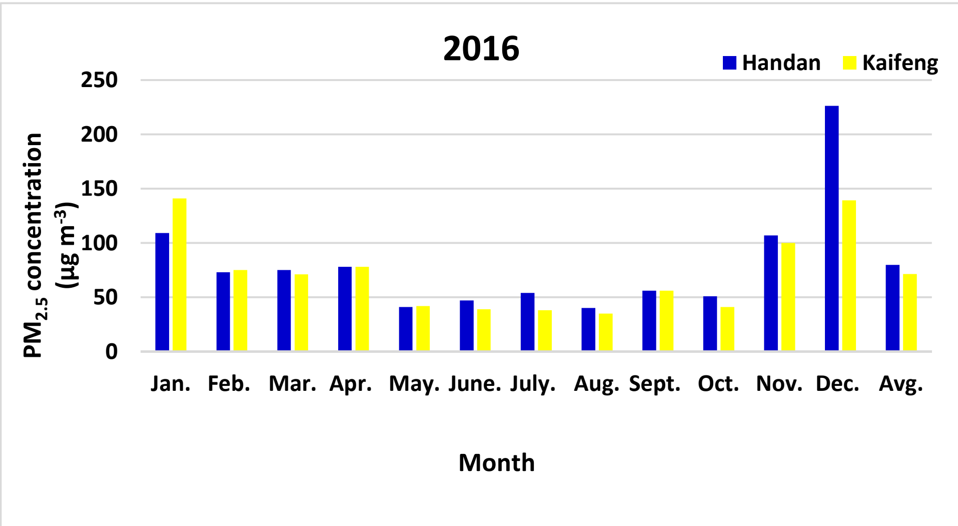

Fig. 2(b). Monthly average atmospheric $PM_{2.5}$ concentration in Handan and Kaifeng during 2016.

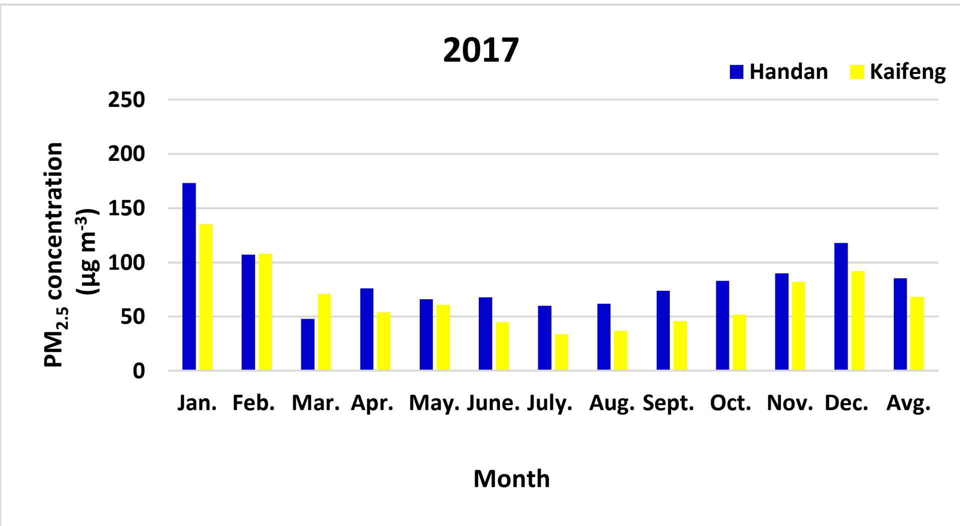

Fig. 2(c). Monthly average atmospheric $PM_{2.5}$ concentration in Handan and Kaifeng during 2017.

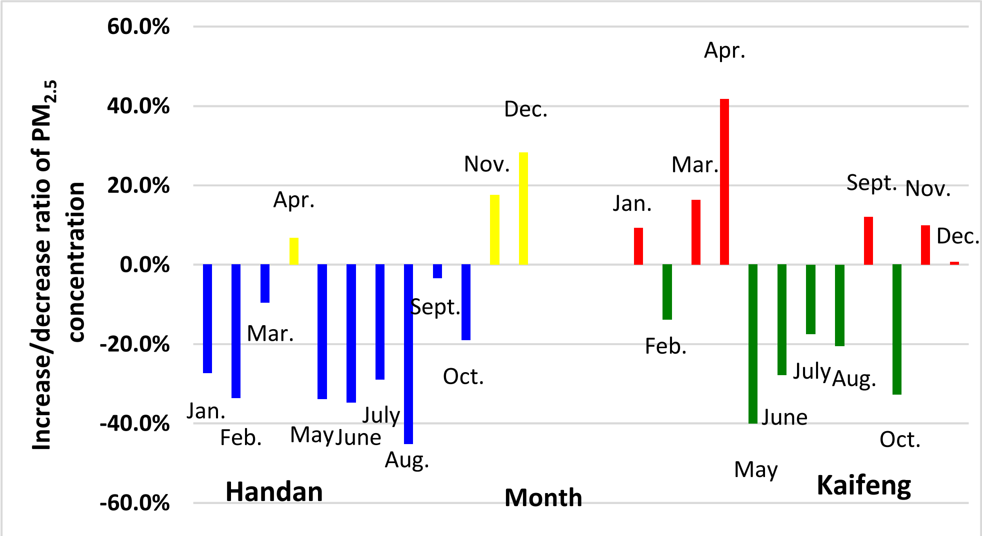

Fig. 2(d). Increase/decrease of $PM_{2.5}$ concentration in Handan and Kaifeng during 2015–2016.

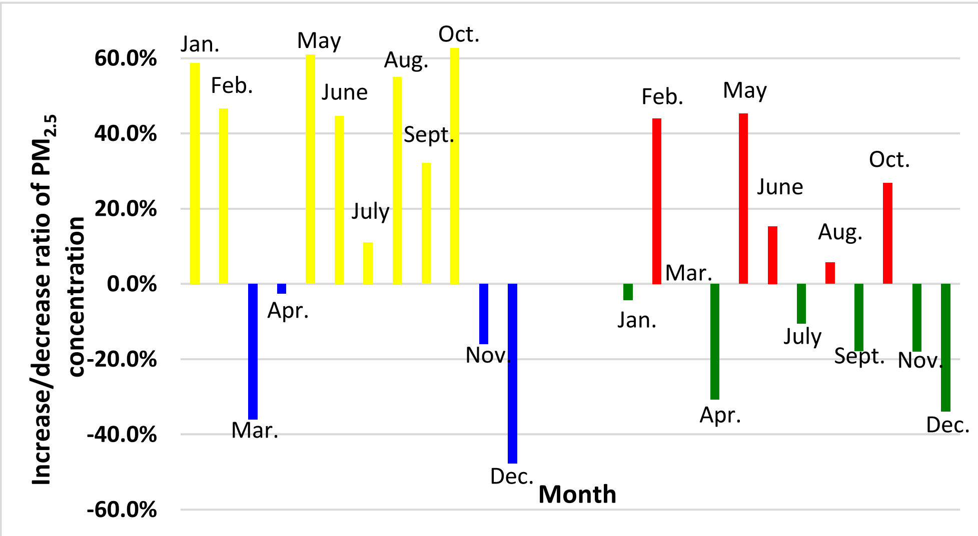

Fig. 2(e). Increase/decrease of $PM_{2.5}$ concentration in Handan and Kaifeng during 2016–2017.

Total PCDD/Fs-WHO2005-TEQ Concentration in Ambient Air

From 2015 to 2017, the total PCDD/Fs-WHO_{2005}-TEQ concentrations in the ambient air of Handan and Kaifeng cities are shown in Fig. 3. In 2015, in Handan, the monthly average total PCDD/Fs-WHO_{2005}-TEQ concentration ranged between 0.066 and 0.169 pg-WHO_{2005}-TEQ m^{-3} and averaged 0.097 pg-WHO_{2005}-TEQ m^{-3}, which was a 3% order of magnitude lower than Baoding City (0.100 pg-WHO_{2005}-TEQ m^{-3}) (Xing *et al.*, 2017); December had the highest concentration (0.169 pg-WHO_{2005}-TEQ m^{-3}), while June had the lowest (0.066 pg-WHO_{2005}-TEQ m^{-3}); in 2016, the monthly average total PCDD/Fs-WHO_{2005}-TEQ concentrations ranged between 0.043 and 0.180 pg-WHO_{2005}-TEQ m^{-3} and averaged 0.089 pg-WHO_{2005}-TEQ m^{-3}, which was a 4.7% order of magnitude higher than Baoding City (0.085 pg-WHO_{2005}-TEQ m^{-3}) (Xing *et al.*, 2017); December had the highest concentration (0.180 pg-WHO_{2005}-TEQ m^{-3}), while August had the lowest (0.043 pg-WHO_{2005}-TEQ m^{-3}); in 2017, the monthly average total PCDD/Fs-WHO_{2005}-TEQ concentrations ranged from 0.045 to 0.162 pg-WHO_{2005}-TEQ m^{-3} and averaged 0.092 pg-WHO_{2005}-TEQ m^{-3}. January had the highest concentration (0.162 pg-WHO_{2005}-TEQ m^{-3}), while July had the lowest (0.045 pg-WHO_{2005}-TEQ m^{-3}).

In 2015, in Handan, the seasonal variations in total PCDD/Fs-WHO_{2005}-TEQ concentrations were 0.099, 0.070, 0.083 and 0.136 pg-WHO_{2005}-TEQ m^{-3} in spring, summer, autumn, and winter, respectively; in 2016, the concentrations were 0.099, 0.046, 0.092 and 0.118 pg-WHO_{2005}-TEQ m^{-3}, respectively, and in 2017, the concentrations were 0.101, 0.057, 0.085 and 0.126 pg-WHO_{2005}-TEQ m^{-3}, respectively. It can be seen that the total PCDD/Fs-WHO_{2005}-TEQ concentration exhibits obvious seasonal variations, where the total PCDD/Fs-WHO_{2005}-TEQ concentration is generally the largest in winter and smallest in summer.

In Kaifeng, in 2015, the monthly average total PCDD/Fs-

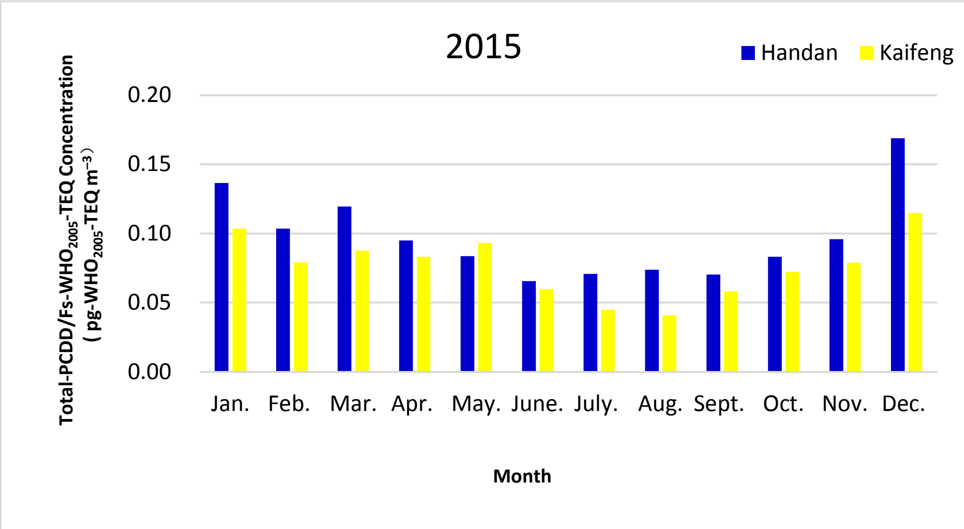

Fig. 3 (a). Monthly average total-PCDD/Fs-WHO_{2005}-TEQ concentration in Handan and Kaifeng during 2015.

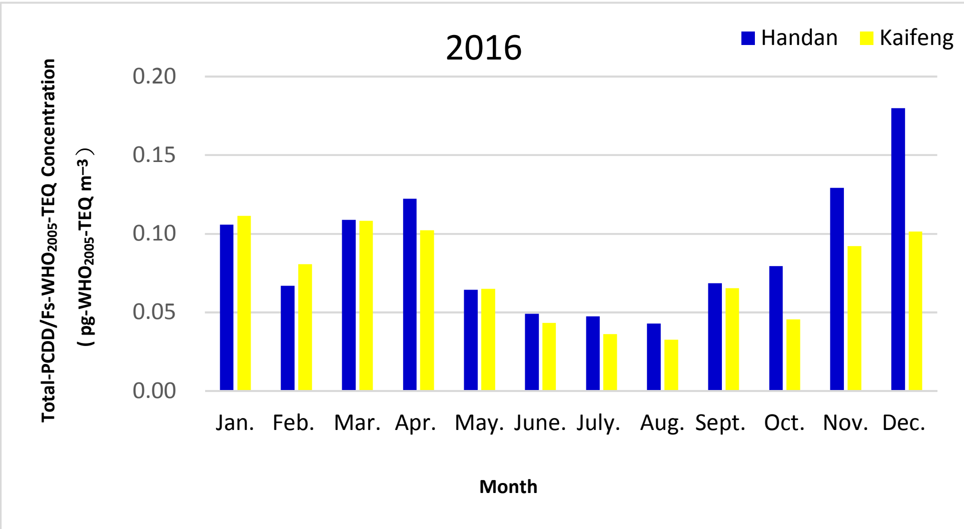

Fig. 3(b). Monthly average total-PCDD/Fs-WHO_{2005}-TEQ concentration in Handan and Kaifeng during 2016.

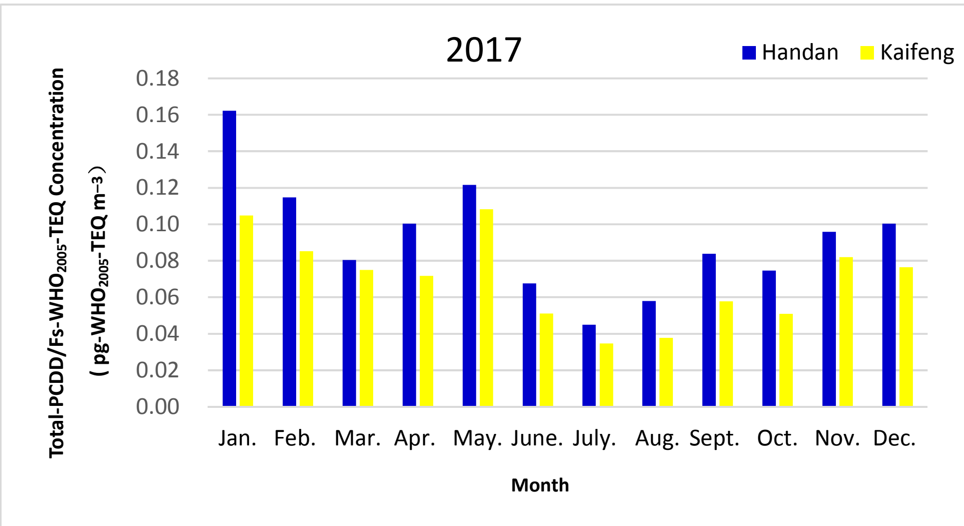

Fig. 3(c). Monthly average total-PCDD/Fs-WHO_{2005}-TEQ concentration in Handan and Kaifeng during 2017.

WHO_{2005}-TEQ concentrations ranged between 0.041 and 0.115 pg-WHO_{2005}-TEQ m^{-3} and averaged 0.076 pg-WHO_{2005}-TEQ m^{-3}, which was a 20.8% order of magnitude lower than Zhengzhou City (0.096 pg-WHO_{2005}-TEQ m^{-3}) (Xing *et al.*, 2017); December had the highest concentration (0.115 pg-WHO_{2005}-TEQ m^{-3}), and August had the lowest (0.041 pg-WHO_{2005}-TEQ m^{-3}); in 2016, the monthly average total PCDD/Fs-WHO_{2005}-TEQ concentrations ranged from 0.033 to 0.111 pg-WHO_{2005}-TEQ m^{-3} and averaged 0.074 pg-WHO_{2005}-TEQ m^{-3}, which was a 10.8% order of magnitude higher than Zhengzhou City (0.083 pg-WHO_{2005}-TEQ m^{-3}) (Xing *et al.*, 2017); January had the highest concentration (0.111 pg-WHO_{2005}-TEQ m^{-3}); in 2017, the monthly average total PCDD/Fs-WHO_{2005}-TEQ concentrations ranged between 0.035 and 0.108 pg-WHO_{2005}-TEQ m^{-3} and averaged 0.070 pg-WHO_{2005}-TEQ m^{-3}. May had the highest concentration (0.108 pg-WHO_{2005}-TEQ m^{-3}), and July had the lowest (0.035 pg-WHO_{2005}-TEQ m^{-3}).

In 2015, in Kaifeng, the seasonal variations in total PCDD/Fs-WHO_{2005}-TEQ concentrations were 0.088, 0.049, 0.070 and 0.099 pg-WHO_{2005}-TEQ m^{-3} in spring, summer, autumn, and winter, respectively; in 2016, they were 0.092, 0.037, 0.068 and 0.098 pg-WHO_{2005}-TEQ m^{-3} , respectively; and in 2017, they were 0.085, 0.041,0.064 and 0.089 pg-WHO_{2005}-TEQ m^{-3} , respectively. This also verifies that the maximum value for the total PCDD/Fs-WHO_{2005}-TEQ concentration mentioned above occurs in winter, and the minimum occurs in summer.

For monthly $PM_{2.5}$ concentrations and the total PCDD/Fs-WHO_{2005}-TEQ concentration in the ambient, it was found that the higher $PM_{2.5}$ value results in a higher total PCDD/Fs-WHO_{2005}-TEQ concentration (Xing *et al.*, 2017). The concentration of the total PCDD/Fs-WHO_{2005}-TEQ in Handan was found to be higher than that in Kaifeng. On the one hand, the latitude of Handan is higher than that of Kaifeng (Xing *et al.*, 2017; Tang *et al.*, 2017), and on the other hand, it is industrial. Handan is a nationally important iron and steel base and has an annual production capacity of 40 million tons. The ranking table of the PCDD/Fs emission sources in the world are presented in Lu *et al.* (2008), where it can be seen that the production processes for steel and other metals in China ranked first as emission sources of PCDD/Fs. Therefore, the total PCDD/Fs-WHO_{2005}-TEQ concentrations in Handan are closely related to its high-yielding steel industry. As for the seasonal variations in total PCDD/Fs-WHO_{2005}-TEQ concentrations, the highest concentrations were in winter and the lowest were in summer, which is also related to the consumption of heating coal and atmospheric inversion that occurs in winter.

According to the figure analyses, the total PCDD/Fs-WHO_{2005}-TEQ concentrations in the ambient air of Kaifeng are decreasing annually. In addition, the number of motor vehicles has been increasing in Handan. Every year, Hebei Province has added more than 3 million motor vehicles, and this number has continued to grow for the past eight years. In Handan, the number of motor vehicles in the second quarter of 2015 was 1,630,426 units; at the end of 2016, the number of vehicles was 1,665,187 units. Quaβ (2004) pointed out that, comparing the PCDD/F of European vehicle emissions with other sources of PCDD/Fs (the second largest source being boiler furnaces), although PCDD/Fs from European vehicular emissions are not the major sources of emissions, they do have a significant influence on environmental quality and contribute about 2% of the total emissions (Quaβ *et al.*, 2004).

$PM_{2.5}$-Bound Total PCDD/Fs-WHO_{2005}-TEQ content

The contribution of the total PCDD/Fs-WHO_{2005}-TEQ concentration in ambient air mainly comes from the particle phase (the contribution of the particle phase ranged from 58.6% to 94.3%). Previous studies in Asian countries have shown that the total PCDD/Fs-WHO_{2005}-TEQ concentrations for the particle phase in summer account for 36.4%–71.5% of their total concentrations (Hayakawa *et al.*, 2004). More than 90% of the PCDD/F studies on the ambient environment have proposed that the PCDD/F mass is mainly concentrated in the particulate phase (Lee *et al.*, 2008). $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ contents in Handan and Kaifeng cities from 2015 to 2017 are shown in Fig. 4. In the case of Handan, the annual average $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ content was 0.63, 0.65 and 0.63 ng WHO_{2005}-TEQ g^{-1} in 2015, 2016, and 2017, respectively, with an average 0.64 ng WHO_{2005}-TEQ g^{-1}. However, in Kaifeng, the annual average $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ content was 0.58, 0.58 and 0.54 ng WHO_{2005}-TEQ g^{-1} in 2015, 2016, and 2017, respectively, and averaged 0.57 ng WHO_{2005}-TEQ g^{-1}, which was approximately an 11.4% order of magnitude lower than that in Handan.

In Handan, the three-year monthly average $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ content from January to December in order was 0.74, 0.74, 1.07, 0.83, 0.73, 0.32, 0.23, 0.31, 0.45, 0.74, 0.82, and 0.68 ng WHO_{2005}-TEQ g^{-1}, respectively. The highest level occurred in March (1.07 ng WHO_{2005}-TEQ g^{-1}) and was a 4.7 order of magnitude higher than that of the lowest level, which occurred in July (0.23 ng WHO_{2005}-TEQ g^{-1}). In Handan, the three-year average $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ content in spring, summer, autumn, and winter was 0.88, 0.28, and 0.67 and 0.72 ng WHO_{2005}-TEQ g^{-1}, respectively, which showed that in spring (0.88 ng WHO_{2005}-TEQ g^{-1}) to be a 3.1 order of magnitude higher than that in summer (0.28 ng WHO_{2005}-TEQ g^{-1}).

As for Kaifeng, the three-year monthly average $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ content from January to December in sequence was 0.61, 0.69, 0.92, 0.79, 0.70, 0.34, 0.20, 0.24, 0.40, 0.58, 0.66, and 0.65 ng WHO_{2005}-TEQ g^{-1}, respectively, which showed that the highest level occurred in March (0.92 ng WHO_{2005}-TEQ g^{-1}) and was approximately a 4.6 order of magnitude higher than that of the lowest one, which occurred in July (0.20 ng WHO_{2005}-TEQ g^{-1}). Seasonal variations in the three-year average $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ content in spring, summer, autumn, and winter were 0.80, 0.26, 0.55, and 0.65 ng WHO_{2005}-TEQ g^{-1}, respectively, which indicated that of spring (0.80 ng WHO_{2005}-TEQ g^{-1}) to be a 3.1 order of magnitude higher than that in summer (0.26 ng WHO_{2005}-TEQ g^{-1}).

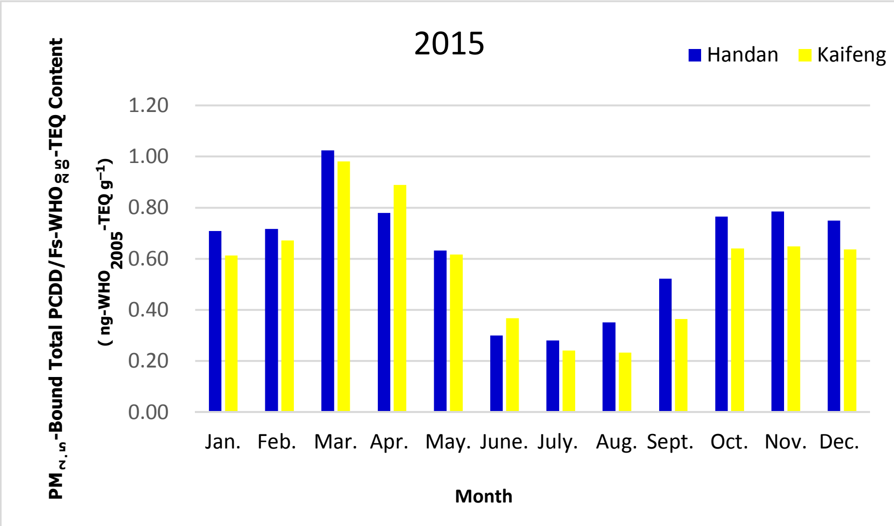

Fig. 4(a). $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ Content (ng-WHO_{2005}-TEQ g^{-1}) of Handan and Kaifeng during 2015.

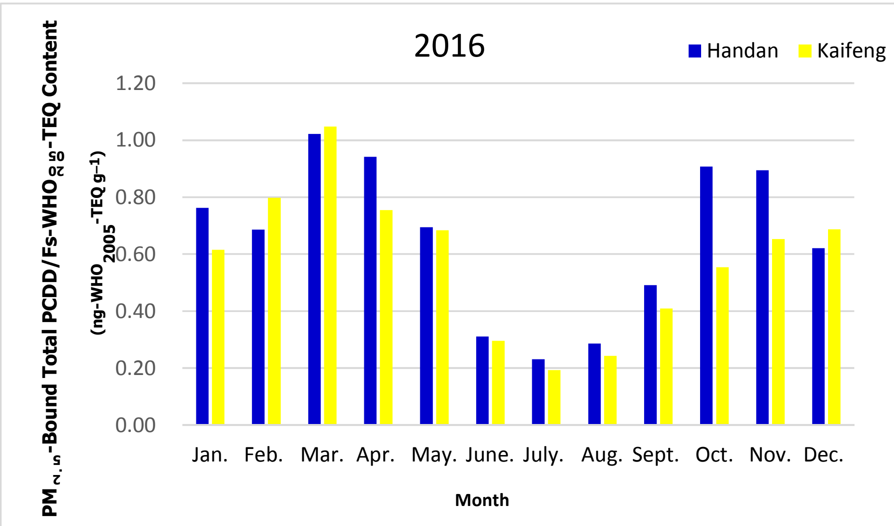

Fig. 4(b). $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ content (ng-WHO_{2005}-TEQ g^{-1}) of Handan and Kaifeng during 2016.

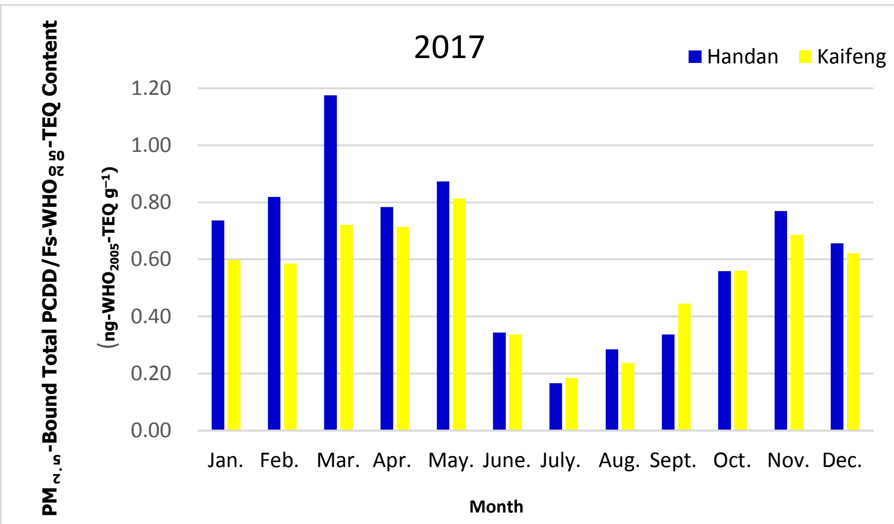

Fig. 4(c). $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ content (ng-WHO_{2005}-TEQ g^{-1}) of Handanand Kaifeng during 2017.

A comparison of the seasonal variations in the $PM_{2.5}$-bound total PCDD/Fs-WHO2005-TEQ content indicates that between 2015 and 2017 in Handan, the average $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ content in summer was approximately only 58.2%, 64.6%, and 64.5% lower than the average value of the other three seasons (spring, autumn, and winter), respectively. In Kaifeng, from 2015–2017, the $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ content in summer was approximately only 58.3%, 64.6%, and 60.4% lower than the average value of the other three seasons (spring, autumn, and winter), respectively. From 2015–2017, the average temperature in the summer (26.9°C) for the three years under investigation in Handan was much higher than that in spring (16.8°C), autumn (15.5°C), and winter (2.4°C), which was very similar in Kaifeng, where from 2015–2017, the average temperature in the summer (27.3°C) was also much higher than that in spring (17.3°C), autumn (16.2°C), and winter (4.2°C). As the temperature rose, a greater amount of PCDD/F mass evaporated from the particle to the gaseous phase, resulting in a lower $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ content (Xing *et al*., 2017).

Gas-Particle Partitioning of PCDD/Fs

The gas-particle partitioning of PCDD/F and other POPs is an important factor that influences the efficiency of atmospheric removal by wet and dry deposition (Bidleman *et al*., 2000; Cheruiyot *et al*., 2015, 2016; Redfern *et al*., 2017). When PCDD/Fs are emitted into the atmosphere, they have a specific distribution between the gas and particle phases based on their concentrations, the atmospheric temperature, vapor pressure, and the ambient air particulate concentration (Hoff *et al.*, 1996). Here, the gas-particle partitioning was calculated from the atmospheric temperature using Eq. (1), Eq. (2), and Eq. (3), and the seasonal gas-particle partitioning of total PCDD/Fs-WHO_{2005}-TEQ in the ambient air in Handan and Kaifeng from 2015–2017 is shown in Fig. 5. It can be clearly seen that the gas-particle partitioning of PCDD/F exhibits obvious seasonal variations. In Handan, from 2015–2017, the three-year average temperatures in spring, summer, autumn, and winter were 16.8, 26.9, 15.5, and 2.4°C, respectively. As for the seasonal variations in gas-particle partitioning, the average fractions of gas phase total PCDD/Fs-WHO_{2005}-TEQ concentrations in spring, summer, autumn, and winter were 26.4%, 62.8%, 28.9% and 3.3%, respectively. In Kaifeng, from 2015–2017, the seasonal average temperatures were 17.3, 27.3, 16.2, and 4.2°C in spring, summer, autumn, and winter, respectively; the average fractions of gas phase total PCDD/Fs-WHO_{2005}-TEQ concentrations in spring, summer, autumn, and winter were 17.3%, 27.3%, 16.2%, and 4.2%, respectively. The above results indicate that the fractions of gas phase total PCDD/Fs-WHO_{2005}-TEQ in both cities in summer were all higher than those in the gas phase in spring, autumn, and winter. A similar conclusion has been drawn in previous studies suggesting that gas phase PCDD/Fs have higher fractions in summer than in winter (Wang *et al.*, 2010; Huang *et al*., 2011; Lee *et al*., 2016).

Regression Analysis

A regression analysis is used to study the calculation method and theory for the specific dependency of one variable on another variable. In this study, the daily AQI values for Handan and Kaifeng cities were collected and compiled from 2015 to 2017 on the website of the Ministry of Environmental Protection of the People's Republic of China. The AQI for Handan City and Kaifeng City was taken as the X axis, and the total PCDD/Fs-WHO_{2005}-TEQ concentration was taken as the Y axis. A confidence level of 95% was set up to establish the linear regression analysis chart. The regression equations for three years, respectively, were $Y = 2.83 \times 10^{-6} + 6.96 \times 10^{-4}X$, $Y = -3 \times 10^{-3} + 7.02 \times 10^{-4}X$, and $Y = -8.85 \times 10^{-4} + 6.61 \times 10^{-4}X$, respectively. As shown in Fig. 6, there are positive correlations between the AQI and the total PCDD/Fs-WHO_{2005}-TEQ concentration in ambient air. The R^2 values in 2015, 2016, and 2017 were 0.929, 0.921, and 0.876, respectively. The AQI can be used to roughly predict the total PCDD/Fs-WHO_{2005}-TEQ concentration in ambient air through a regression equation. For example, in 2015, the AQI values in Handan City and Kaifeng City ranged from 100 to 200, the corresponding total PCDD/Fs-WHO_{2005}-TEQ concentration of about 0.1 to 0.2 pg-WHO_{2005}-TEQ m^{-3}. It can be seen from the figure that the distribution of data in 2016 is relatively uniform. The AQI values of 200 to 300 are also distributed, indicating that there are more moderate pollution days in 2016 and air pollution is more serious.The trend of data distribution in 2017 is similar to that of 2016. However, the value of the AQI in 2017 is mostly concentrated between 100 and 150, the numbers of days with good air quality is more, the maximum AQI for both 2015 and 2016 were all close to 500 and the maximum AQI did not exceed 400 during 2017, which showed the total PCDD/Fs-WHO_{2005}-TEQ concentration was approximately 0.3 pg-WHO_{2005}-TEQ m^{-3} is not more than 2015 and 2016 of the maximum, indicating that the air quality of 2017 is better than that of 2015 and 2016.

CONCLUSION

The three-year average $PM_{2.5}$ concentration in Handan (85.3 µg m^{-3}) was 1.2 times of magnitude higher than that in Kaifeng (71.1 µg m^{-3}). The total PCDD/Fs-WHO_{2005}-TEQ concentration in Handan (0.093 pg-WHO_{2005}-TEQ m^{-3}) was 1.3 times of magnitude higher than that in Kaifeng (0.073 pg-WHO_{2005}-TEQ m^{-3}). This may relate to the high-yielding steel industry in Handan. The higher consumption of heating coal and atmospheric inversion that occurs in winter resulted in winter exhibited the highest PCDD/Fs-WHO_{2005}-TEQ concentrations in these two cities. The higher temperature in summar cause lower $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ content compared to those in winter. Furthermore, highly positive correlations between the AQI and the total PCDD/Fs-WHO_{2005}-TEQ concentration were found and the AQI can be used to roughly predict the level of total PCDD/Fs-WHO_{2005}-TEQ in ambient air through the use of a regression equation in these two cities.

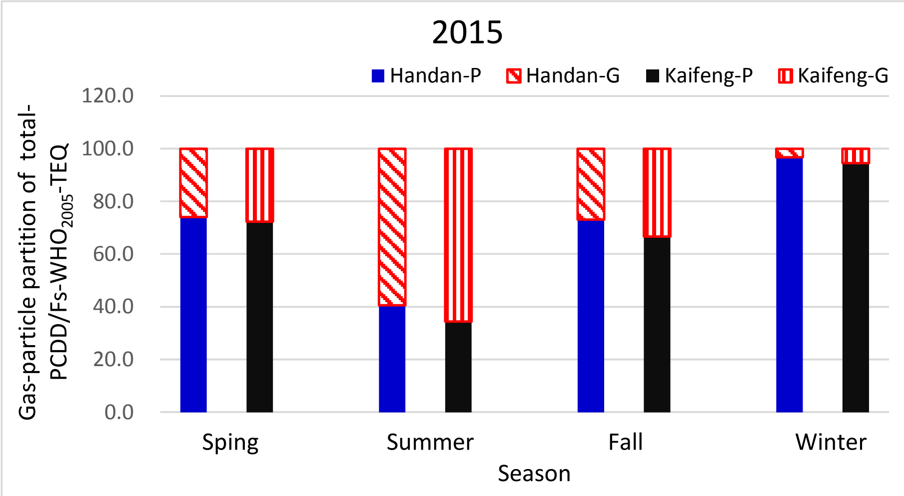

Fig. 5(a). Seasonal variations of gas-particle partition of total-PCDD/Fs-WHO$_{2005}$-TEQ in the ambient air in Handan and Kaifeng during 2015.

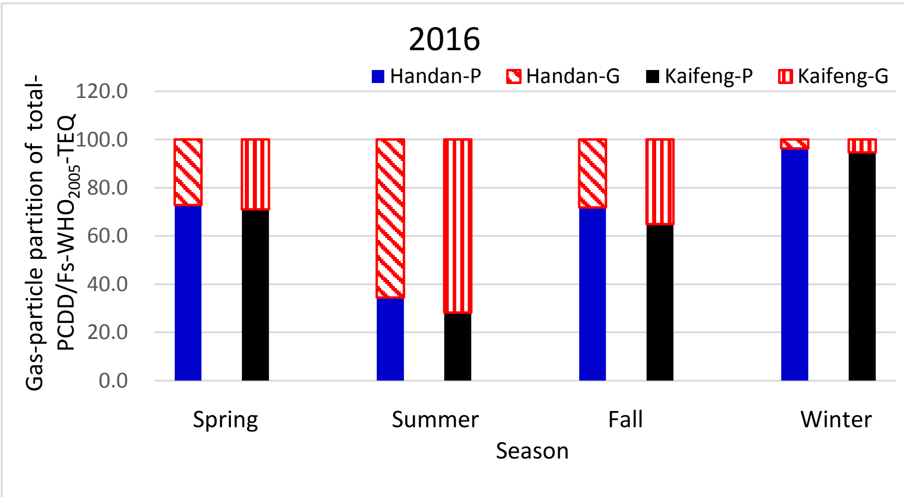

Fig. 5(b). Seasonal variations of gas-particle partition of total-PCDD/Fs-WHO$_{2005}$-TEQ in the ambient air in Handan and Kaifeng during 2016.

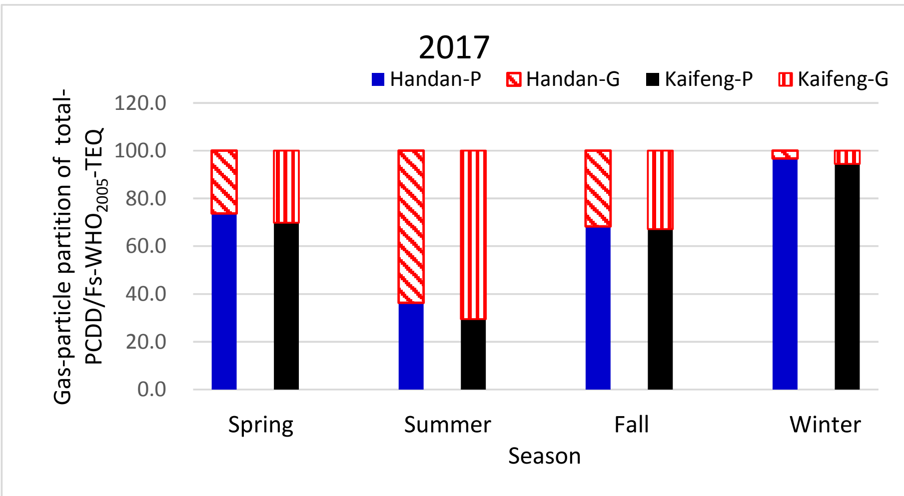

Fig. 5(c). Seasonal variations of gas-particle partition of total-PCDD/Fs-WHO$_{2005}$-TEQ in the ambient air in Handan and Kaifeng during 2017.

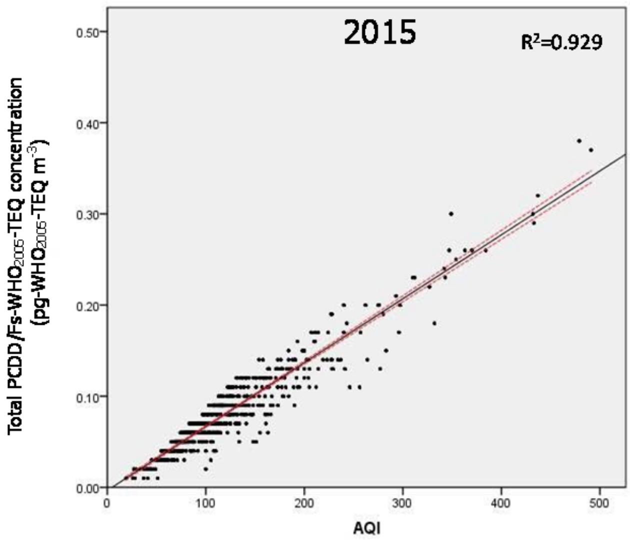

Fig. 6(a). Correlation between AQI and total PCDD/Fs-WHO$_{2005}$-TEQ concentration in ambient air during 2015.

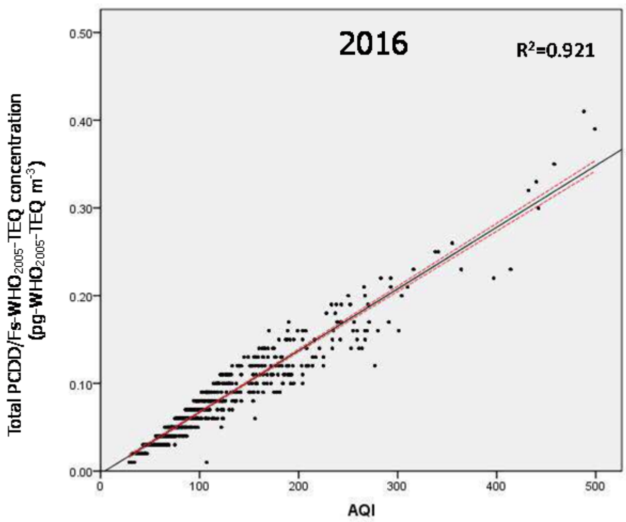

Fig. 6(b). Correlation between AQI and total PCDD/Fs-WHO$_{2005}$-TEQ concentration in ambient air during 2016.

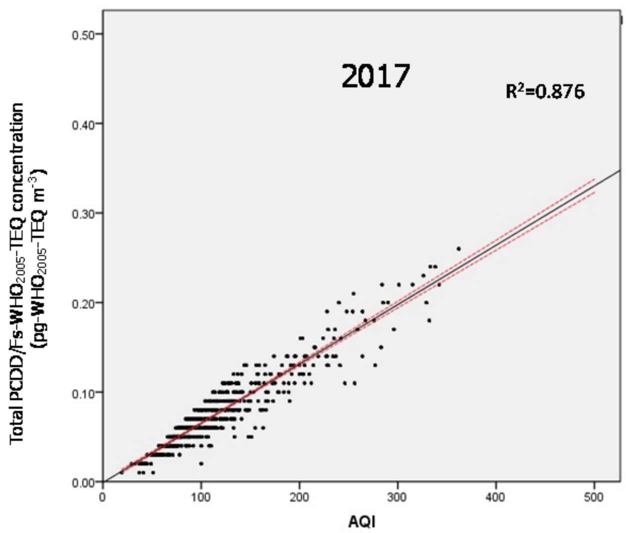

Fig. 6(c). Correlation between AQI and total PCDD/Fs-WHO$_{2005}$-TEQ concentration in Ambient Air during 2017.

REFERENCES

Chao, M.R., Hu, C.W., Chen, Y.L., Chang-Chien, G.P., Lee, W.J., Chang, L.W., Lee, W.S. and Wu, K.Y. (2004). Approaching gas-particle partitioning equilibrium of atmospheric PCDD/Fs with increasing distance from an incinerator: Measurements and observations on modeling. *Atmos. Environ.* 38: 1501–1510.

Chen, Z.H., Cheng, S.Y. and Su, F.Q. (2008). Analysis of weather Types and Transport Routes in North China during Air Pollution. *Res. Environ. Sci.* 21: 17–21.

Cheruiyot, N.K., Lee, W.J., Mwangi, J.K., Wang, L.C., Lin, N.H., Lin, Y.C., Cao, J.J., Zhang, R.J. and Chang-Chien, G.P. (2015). An overview: Polycyclic aromatic hydrocarbon emissions from the stationary and mobile sources and in the ambient air. *Aerosol Air Qual. Res.* 15: 2730–2762.

Cheruiyot, N.K., Lee, W.J., Yan, P., Mwangi, J.K., Wang, L.C., Gao, X., Lin, N.H. and Chang-Chien, G.P. (2016). An overview of PCDD/F inventories and emission factors from stationary and mobile sources: What we know and what is missing. *Aerosol Air Qual. Res.* 16: 2965–2988.

Chow, J.C., Yang, X., Wang, X., Kohl, S.D., Hurbain, P.R., Chen, L.A. and Watson, J.G. (2015). Characterization of ambient PM_{10} bioaerosols in a California agricultural town. *Aerosol Air Qual. Res.* 15: 1433–1447.

Donnelly, J., Munslow, W., Mitchum, R. and Sovocool, G. (1987). Correlation of structure with retention index for chlorinated dibenzo-*p*-dioxins. *J. Chromatogr.* 392: 51–63.

Fiedler, H. and Hutzinger, O. (1992). Sources and sinks of dioxins: Germany. *Chemosphere* 25: 1487–1491.

Ghosh, S., Gupta, T., Rastogi, N., Gaur, A., Misra, A., Tripathi, S.N., Paul, D., Tare, V., Prakash, O. and Bhattu, D. (2014). Chemical characterization of summertime dust events at Kanpur: Insight into the sources and level of mixing with anthropogenic emissions. *Aerosol Air Qual. Res.* 14: 879–891.

Hale, M.D., Hileman, F.D., Mazer, T., Shell, T.L., Noble, R.W. and Brooks, J.J. (1985). Mathematical modeling of temperature programmed capillary gas chromatographic retention indexes for polychlorinated dibenzofurans. *Anal. Chem.* 57: 640–648.

Hao, J.M., Cheng, Z. and Wang, S.X. (2012). Research on the status of atmospheric environmental pollution and prevention and control measures in China. *Environ. Prot.* 9: 16–20.

Hayakawa, K., Takatsuki, H. and Watanabe, L. (2004). Polybrominated diphenyl ethers (PBDEs), polybrominated dibenzo-*p*-dioxins/dibenzofurans (PBDD/Fs) and monobromo-polychlorinated dibenzo-*p*-dioxins/dibenzofurans (MOBPXDDIFS) in the atmosphere and bulk deposition in Kyoto, Japan. C*hemosphere* 57: 343–356.

http://datacenter.mep.gov.cn/

https://www.airnow.gov/

https://www.epa.gov/

https://www.wunderground.com/

Huang, C.J., Chen, K.S., Lai, Y.C., Wang, L.C. and Chang-Chien, G.P. (2011). Characterization of atmospheric dry deposition of polychlorinated dibenzopdioxins/ dibenzofuran in a rural area of Taiwan. *Aerosol Air Qual. Res.* 11: 448–459.

Hung, H., Blanchard, P., Poole, G., Thibert, B. and Chiu, C.H. (2002). Measurement of particle-bound polychlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDD/Fs) in Arctic air at Alert, Nunavut, Canada. *Atmos. Environ.* 36: 1041–1050.

International Agency for Research on Cancer (IARC) (1997). *Monographs on the evaluation of carcinogenic risks to humans. Polychlorinated dibenzo-para-dioxins and polychlorinated dibenzofurans.* Vol. 69, IARC Scientific Publ. Lyon, France

Lee, K.L., Lee, W.J., Mwangi, J.K., Wang, L.C., Gao, X and Chang-Chien, G.P. (2016). Atmospheric $PM_{2.5}$ and depositions of polychlorinated dibenzo-*p*-dioxins and dibenzofurans in Kaohsiung area, Southern Taiwan. *Aerosol Air Qual. Res.* 16: 1775–1791.

Lee, R.G.M. and Jones K, C. (1999). Gas-Partitioning of Atmospheric PCDD/Fs: Measurement and observations on modeling. *Environ. Sci. Technol.* 33: 3596–3604.

Lee, S.J., Ale, D., Chang, Y.S., Oh, J.E. and Shin, S.K. (2008). Seasonal and particle size-dependent variations in gas/particle partitioning of PCDD/Fs. *Environ. Pollut.* 153: 215–222.

Li, W.W., Lin, X.Q., Yu, M.F., Mubeen, I., Buekens, A. and Li, X.D. (2016). Experimental study on PCDD/Fs adsorption onto nano-graphite. *Aerosol Air Qual. Res.* 16: 3281–3289.

Li, Y.M. (2008). *Distribution characteristics of persistent organic pollutants in the atmosphere, gas-grain distribution and soil-gas exchange research*. Beijing: Ecological environment research center, Chinese academy of sciences.

Lohmann, R. and Jones, K.C. (1998). Dioxins and furans in air and deposition: A review of levels, behaviour and processes. *Sci. Total Environ.* 219: 53–81.

Lohmann, R., Lee, R.G., Green, N.J. and Jones, K.C. (2000). Gas-particle partitioning of PCDD/Fs in daily air samples. *Atmos. Environ.* 34: 2529–2537.

Lu, H.Y., Lin, S.L., Mwangi, J.K., Wang, L.C. and Lin, H.Y. (2016). Characteristics and source apportionment of atmospheric $PM_{2.5}$ at a coastal city in Southern Taiwan. *Aerosol Air Qual. Res.* 16: 1022–1034.

Lu, Y.H., Huang, J., Yu, G., Yang, X. (2008). International comparative study on China dioxin emission inventory. *Environ. Pollut. Prev.* 30: 71–72.

Mi, H.H., Wu, Z.S., Lin, L.F., Lai, Y.C., Lee, Y.Y., Wang, L.C. and Chang-Chien, G.P. (2012). Atmospheric dry deposition of Polychlorinated dibenzo-pdioxins/dibenzofurans (PCDD/Fs) and Polychlorinated biphenyls (PCBs) in Southern Taiwan. *Aerosol Air Qual. Res.* 12: 1016–1029.

Paustenbach, D.J. (2002). The U.S. EPA Science Advisory Board Evaluation (2001) of the EPA dioxin reassessment. *Regul. Toxicol. Pharm.* 36: 211–219.

Quaß, U., Fermann, M. and Bröker, G. (2004). The European dioxin air emission inventory project—final results. *Chemosphere* 54: 1319–1327.

Redfern, F.M., Lee, W.J., Yan, P., Mwangi, J.K., Wang, L.C. and Shih, C.H. (2017). Overview and perspectives on emissions of polybrominated diphenyl ethers on a global basis: Evaporative and fugitive releases from commercial PBDE mixtures and emissions from combustion sources. *Aerosol Air Qual. Res.* 17: 1117–1131.

Ren, Z.H., Wan, B.T. and Su, F.Q. (2004). Some characteristics of current Atmospheric Environment in China. *Acta Sci. Circum.* 17: 1–6.

Schecter, A., Birnbaum, L., Ryan, J.J. and Constable, J.D. (2006). Dioxins: An overview. *Environ. Res.* 101: 419–428.

Suryani, R.C., Lee, W.J., Endah Mutiara, M.P., Mwangi, J.K., Wang, L.C., Lin, N.H. and Chang-Chien, G.P. (2015). Atmospheric deposition of polychlorinated dibenzo-*p*-dioxins and dibenzofurans at coastal and high mountain areas in Taiwan. *Aerosol Air Qual. Res.* 15: 1390–1411.

Tang, H.Y., Cui, K.P., Xing, J., Zhu, J.N., Lee, W.J., Mwangi, J.K. and Lee, Y.C. (2017). Part I: $PM_{2.5}$ and polychlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDD/Fs) in the ambient air of sorthern China. *Aerosol Air Qual. Res.* 17: 1450–1469.

U.S. Department of Health and Human Services(2000). Public health service, national toxicology program, 9th report on Carcinogens.

Van den Berg, M., Birnbaum, L., Bosveld, A., Brunström, B., Cook, P., Feeley, M., Giesy, J.P., Hanberg, A., Hasegawa, R. and Kennedy, S.W. (1998). Toxic equivalency factors (TEFs) for PCBs, PCDDs, PCDFs for humans and wildlife. *Environ. Health Perspect.* 106: 775–792.

Wang, L.T., Pan, X.M. and Zhang, J. (2012). Simulation of haze pollution in Hebei and its Surroundings. *Acta Sci Circum.* 32: 925–931.

Wang, Y.F., Hou, H.C., Li, H.W., Lin, L.F., Wang, L.C., Chang-Chien, G.P. and You, Y.S. (2010). Dry and wet depositions of polychlorinated dibenzo-*p*-dioxins and dibenzofurans in the atmosphere in Taiwan. *Aerosol Air Qual. Res.* 10: 378–390.

Xing, J., Cui, K.P. Tang, H.Y., Lee, W.J., Wang, L.C., Zhu, J.N. and Huang, Q.L. (2017). Part II: $PM_{2.5}$ and Polychlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDD/Fs) in the ambient air of northern China. *Aerosol Air Qual. Res.* 17: 2010–2026.

Yang, H.Y., Tseng, Y.L., Chuang, H.L., Li, T.C., Yuan, C.S. and Lee, J.J. (2017). Chemical fingerprint and source identification of atmospheric fine particles sampled at three environments at the tip of southern taiwan. *Aerosol Air Qual. Res.* 17: 529–542.

Zhang, P., Tan, S.B. and Wang, L.T. (2012). Monitoring and research on the characteristics of atmospheric particles poluution in Handan. *Acta Sci Circum.* 33: 2679–2685.

Zhou, L., Xu, D.D. and Liu, J.M. (2002). Research progress of dioxin in the atmosphere. *Environ. Pollut. Control Technol. Equip.* 3: 8.

Zhu, J.N., Tang, H.Y., Xing, J., Lee, W.J., Yan, P. and Cui, K.P. (2017). Atmospheric deposition of polychlorinated dibenzo-*p*-dioxins and dibenzofurans in two cities of southern China. *Aerosol Air Qual. Res.* 17: 1798–1810.

Received for review, February 1, 2018
Revised, March 23, 2018
Accepted, March 23, 2018