Emission Characteristics of Volatile Organic Compounds from Typical Coal Utilization Sources: A Case Study in Shanxi of Northern China

Yang Xu1,2†, Hualong Yu1†, Yulong Yan1*, Lin Peng1, Rumei Li1,2, Cheng Wang1,2, Zhiyong Li3

1 MOE Key Laboratory of Resources and Environmental System Optimization, College of Environmental Science and Engineering, North China Electric Power University, Beijing 102206, China
2 School for Energy, Power and Mechanical Engineering, North China Electric Power University, Beijing 102206, China
3 School of Environmental Science and Engineering, North China Electric Power University, Baoding 07100, China

ABSTRACT

China, where coal is the dominant energy resource, accounted for 50.5% of the world’s coal consumption—or 1906.7 million tons of oil equivalent—during 2018. As a major source of volatile organic compounds (VOCs), coal utilization also led to high national emissions of these pollutants. In this study, we investigated the profiles; benzene, toluene, ethylbenzene, and xylene (BTEX) ratios; ozone formation potential (OFP); and secondary organic aerosol (SOA) formation potential of VOCs generated by coal-utilizing steel plants, power plants, coking plants, and residential stoves in northern China. Among the detected VOCs, the results identified 1-butene as the most abundant species for both the power plants (36.7%) and the residential stoves (41.7%) as well as a significant contributor at the steel plants (7.3%), and alkenes, alkanes, and aromatics composed the largest groups for the power plants (42.0%) and residential stoves (60.2%); steel plants (59.2%); and coking plants (66.1%), respectively. Additionally, the VOC profiles for power plants employing the same coal source or combustion technology exhibited strong similarities, although the BTEX ratios varied more between plants using different coal sources than those using different combustion technologies. Finally, alkenes were primarily responsible for the ozone formation (73.1%, 59.0%, and 87.6% for the power plants, steel plants, and residential stoves, respectively), whereas aromatics were primarily responsible for the SOA formation (more than 94.0% for all four coal-utilizing sources).

Keywords: Volatile organic compounds, Source profiles, BTEX, Ozone formation potential, Coal utilization source

1 INTRODUCTION

The tropospheric ozone concentration in China has continually increased in recent years. Compared to 2018, the average concentrations of PM$_{2.5}$, PM$_{10}$, SO$_2$, NO$_2$, and CO in 337 major cities declined in 2019 by 0%, 1.6%, 15.4%, 0%, and 0%, respectively, while only ozone concentration increased by 6.5% (Ministry of Ecological Environment, 2020). As the main precursor of ozone, VOC pollution is the main cause of serious tropospheric ozone pollution problems. Moreover, VOCs play an important role in complex atmospheric pollution formation, which is linked to the formation of peroxydes, aldehyde, ketone, peroxyacyl nitrates (PANs), and SOA (Yao et al., 2006). Atmospheric VOCs can also adversely affect human health, plants, animals and the ecological environment (Zou et al., 2013). The U.S. EPA (2020) identified 389 hazardous air pollutants that
initially established, there are still many limitations and concerns regarding the accuracy of these VOC emission characteristics of typical coal usage sources in China have been analyzed by many studies. For instance, Shi et al. (2015) analyzed the VOC emission characteristics of coal utilization processes in five Spanish coal power plants and found that halogenated species emitted during the coal utilization process in five Spanish coal power plants and found that halogenated species were the main VOC species formed during coal utilization. Shi et al. (2015) analyzed the VOC emission characteristics of coal-fired industry plants in Liaoning Province (northern China), and concluded that halogenated hydrocarbons were the representative VOC groups from iron smelt and coke production plants, while aromatics were the largest VOC group from heating stations. Li et al. (2018) studied the VOC emission characteristics of coal-fired coking plants, and power plants in Hebei Province (northern China), and the results showed that benzene, acetylene, and ethane were the three most abundant VOC species emitted from both power plants and coking plants. Santos et al. (2004) analyzed 36 VOC species from the stack gases of coal-fired power stations in Brazil, and found benzene to be the highest VOC species. In southern Taiwan, Tsai et al. (2008) investigated 68 VOC species emitted from four types of technology processes (including coke manufacturing, sintering, hot forming, and cold forming) in an integrated steelworks, and found that toluene, 1,2,4-trimethylbenzene, isopentane, m,p-xylene, 1-butene, ethylbenzene, and benzene were the dominant VOC species in these processes.

Many studies have analyzed the VOC emission characteristics from vehicles (Kawashima et al., 2006; Olson et al., 2009; Yao et al., 2016; Zhang et al., 2016), biomass burning (James et al., 2001; Evtugina et al., 2013; Jumpponen et al., 2013), solvent (Niedojadlo et al., 2007; Yuan et al., 2010; Mo et al., 2015; Tian, 2015), petrochemical (Chen et al., 2006; Zhan, 2015), and refining (Cetin et al., 2003; Lin et al., 2004), but research on VOC emissions from coal utilization sources is limited. In previous studies, Fernández-Martínez et al. (2001) studied the characteristics of 16 VOC species emitted during the coal utilization process in five Spanish coal power plants and found that aromatics, aliphatic hydrocarbons, and chlorinated compounds were the main VOC species formed during coal utilization. Shi et al. (2015) analyzed the VOC emission characteristics of coal-fired industry plants in Liaoning Province (northern China), and concluded that halogenated hydrocarbons were the representative VOC groups from iron smelt and coke production plants, while aromatics were the largest VOC group from heating stations. Li et al. (2018) studied the VOC emission characteristics of coal-fired coking plants, and power plants in Hebei Province (northern China), and the results showed that benzene, acetylene, and ethane were the three most abundant VOC species emitted from both power plants and coking plants. Santos et al. (2004) analyzed 36 VOC species from the stack gases of coal-fired power stations in Brazil, and found benzene to be the highest VOC species. In southern Taiwan, Tsai et al. (2008) investigated 68 VOC species emitted from four types of technology processes (including coke manufacturing, sintering, hot forming, and cold forming) in an integrated steelworks, and found that toluene, 1,2,4-trimethylbenzene, isopentane, m,p-xylene, 1-butene, ethylbenzene, and benzene were the dominant VOC species in these processes.

Scholars (Liu et al., 2008a; Mo et al., 2016; Wu and Xie, 2017) have already conducted significant research on VOC emission characteristics from different VOC emission sources and regions. Although the VOC emission characteristics of typical coal usage sources in China have been initially established, there are still many limitations and concerns regarding the accuracy of these
VOC source profiles: The types of investigated VOC emission sources are limited and insufficient, the measurement and analysis methods of the source profiles are not unified, and species selected for VOC source profiles are not consistent. VOC source profiles represent the chemical composition of VOC species and the relative contribution of a certain source, which can be used to identify the VOC emission sources and evaluate their influence on ozone formation. Previous studies (Mo et al., 2014; Hu, 2017; Huang et al., 2020) identified significant differences between some VOC source profiles from the same industrial emission source due to various factors, such as differences in technology and raw material. Relevant research (Mo et al., 2016; Wu and Xie, 2017) also identified regional differences in VOC emission characteristics. Therefore, a systematic, standard and localized VOC source profile database is required to better understand the VOC characteristics of typical emission sources and solve current photochemical smog and ozone pollution problems. In this study, we investigated the VOC characteristics in five coal-fired power plants with different coal source usages and different coal combustion technologies. These findings have not been reported in previous studies. This study also collected VOC samples from two steel plant production stages to produce more refined VOC profiles from steel plants. We also conducted a comparative analysis of VOC profiles between four different coal utilization processes. The emission characteristics of VOCs from various coal utilization processes (coal-fired power plants, steel plants, coking plants, and residential stoves) were investigated in this study. The research objectives were to (1) conduct a comparative analysis of VOC source profiles from four types of coal utilization processes, (2) calculate BTEX ratios to identify the emission sources, (3) study the ozone formation potential of individual VOC species to investigate their influence on atmospheric ozone, and (4) estimate the SOA formation potential of VOC species emitted from coal utilization processes.

2 METHODS

The study area, Shanxi Province, is a typical coal consumption province in China. This province only accounts for 1.6% of China’s land area but contributes approximately 11.8% of the total national coal consumption (National Bureau of Statistics, 2019). In this study, three types of industrial coal utilization processes (coking plants, steel plants, and power plants) and rural residential coal utilization processes were chosen to investigate the VOC emission characteristics in northern China.

2.1 Basic Information

Thermal power generation was the main electricity supply in China in 2019, accounting for 64.2% of the total electricity production, while coal-fired power plants accounted for 96.8% of the total thermal power generation (China Electricity Council, 2020). Five coal-fired power plants were selected in this study, which covered the two main types of power plant coal-burning boilers: Three power plants adopted pulverized coal-fired boiler technology, and two power plants adopted circulating fluidized bed technology (Ma et al., 2015). China is the largest steel producer and consumer in the world. In steel plants, sintering and blast furnace ironmaking emit a significant mass of pollutants, including VOCs, for coal utilization. VOC samples were collected from both sintering and blast furnace ironmaking processes to study the emission composition characteristics of the steel plant stack exhaust gas. Cokemaking is another important VOC emission source in China; therefore, the flue gas from the coke oven of coking oven plants was also collected to analyze the VOC characteristics. In this study, we also investigated the VOC emission characteristics of rural cooking and heating stoves. The unqualified coal, low combustion efficiency, lack of dedusting and desulfurization facilities of rural stoves could result in serious atmospheric VOC pollution and even indoor air pollution. Detailed information on the chosen VOC emission sources is presented in Table 1.

2.2 Sampling Collection

The sample sites were located in exhaust chimneys or pollutant-monitoring points. VOC samples were collected using 1 L Tedlar bags. The studied compound concentration should be lower than the detection limit of the method. The VOC sample was collected into the sampling
bag using a sampling pump with a flow rate of 0.5 L min⁻¹. The joint between the pump and pipe of the Tedlar sampling bag was airtight during sampling. Close the valve and label the Tedlar bag after sampling. Relevant sampling information was recorded for the subsequent analyses. After sampling, the samples were preserved in the laboratory at room temperature and in the absence of light. All samples were analyzed within 72 hours. The detailed sampling methods are as follows.

2.2.1 Coal-fired power plant
The pollutant-monitoring points of exhaust chimney in power plants were chosen to be sampling sites, which were about 10 m from the ground. A total of 12 samples were collected in the coal-fired power plants.

2.2.2 Steel plant
The pollutant-monitoring points of sintering and blast furnaces in steel plants were chosen to be sampling sites, which were about 15 m from the ground. As the water content of flue gas is relatively high in steel plants, a water absorption device was adopted for dehumidification. A total of 6 samples were collected in the steel plants.

2.2.3 Coking plant
The flue gas samples from air outlet of coke oven were collected in coking plant. A total of 6 samples were collected in the coking plants.

2.2.4 Residential stove
The flue gas samples were collected directly from the chimney of residential coal-fired heating or cooking stoves by using sampling pipe and pump. The height of sample sites was 5 m from ground. A total of 3 samples were collected.

2.3 Sample Analysis
VOC analysis was conducted using the U.S. EPA TO-15 method. The sample was analyzed by preconcentration (Model 7100; Entech Instruments) combined with Gas Chromatography-Mass Spectrometer (6890 GC/5973 MSD; Agilent). 300 mL of gas from the sample bags or canister were pumped into the preconcentrator and
injected into the GC/MS through a preconcentration sampling system. With super-pure helium as the carrier gas, HP-VOC capillary column chromatography (film thickness of 60 m × 0.32 mm × 1.8 mm; Agilent) was used to isolate the compounds. The GC oven temperature was set to 40°C, held for 2 min, then increased to 220°C at a rate of 5°C min⁻¹, holding for 2 min.

Based on electron ionization (EI), MSD runs were conducted in the scanning data acquisition mode, and the mass range was set to 35–300 amu. The method detection limit was less than 0.1 ppbv, and the repeatability was less than 10%. The detected variation in the same standard sample was less than 10%.

The target VOCs were identified according to retention time and standard mass spectrometry and then quantitatively analyzed using the external standard method. The standard gas mixture (1.0 ppm) was diluted with zero air and then sampled and analyzed under the same conditions as the field samples. A seven-point calibration curve (0.0, 1.0, 5.0, 10.0, 50.0, 100.0 and 200.0 ppbv) was used to quantitatively analyze the VOCs in air samples.

2.4 Quality Assurance and Quality Control

Before sampling, the pipe was purged with clean air to remove any impurities from the pipe surface. The pipe was inflated with the sample gas and connected to the VOC sampling device for sampling after the pipe was filled with smoke.

The pipelines of the VOC sampling system are made of Teflon materials for reducing the adsorption effect of the sampling pipe on VOC components. The sampling flowmeter was calibrated before sample collection to ensure the accuracy and stability of the flow rate.

The Tedlar sampling bags were washed at least five times before sampling. At least 1 of the 10 samples was injected with high-purity nitrogen to confirm the effectiveness of cleaning. The VOCs should be undetected or below the detection limit during the cleaning verification experiment. Before every VOC sample analysis, a blank test with high-purity nitrogen was conducted to ensure that the instrument system was not contaminated.

When drawing the standard curve, the relative standard deviation (RSD) of the response factors of each VOC species was less than 30%. A total of 47 species were analyzed in this study, and “total VOCs” refers to the sum of the 47 VOCs.

2.5 Data Analysis

According to the target list developed by the U.S. EPA Photochemical Assessment Monitoring Stations (PAMS) program, the VOC species in this study were selected based on their reactivity to photochemical smog and tropospheric ozone formation. The OFP is related to the chemical reaction activity of VOCs in the atmosphere, and three main methods are typically used to research organic reactivity at the current level: the propylene-equivalent concentration method, OH radical reactivity method, and maximum increment reactivity method (MIR). The former two methods only consider the OH radical and VOC reaction rate and ignore the complicated subsequent reaction. The MIR coefficient method was selected to calculate the OFP of VOCs in this study because it is more objective with regards to the ozone formation reaction mechanism (Cheng et al., 2012). The MIR coefficient method can be used to identify VOC species with high chemical reactivity because the MIR value refers to the ozone formation ability of VOC species under optimum reactive conditions.

The OFP of 47 VOC species were calculated by Eq. (1):

\[
\text{OFP}_i = C_i \times \text{MIR}_i
\]  

where OFP, is the ozone formation potential of VOC species \(i\) (µg-ozone m⁻³); \(C_i\) is the mass concentration of VOC species \(i\) (µg m⁻³); MIR, is the corresponding maximum increment reactivity of VOC species \(i\) (µg-ozone m⁻³) (Carter, 2010).

The fractional aerosol coefficient (FAC) was used to calculate the potential formation of SOA of VOCs. The SOA formation potential of 18 VOC species were calculated by Eq. (2):

\[
\text{SOA}_\text{F} = \text{VOC}_0 \times \text{FAC}
\]  

where SOA, is the SOA formation potential of VOC species (µg m⁻³); VOC₀ is the initial mass
concentration or emissions of VOC species (µg m⁻³); FAC is the corresponding fractional aerosol coefficient of VOC species (Grosjean, 1992; Lv et al., 2009).

3 RESULTS AND DISCUSSION

3.1 VOCs Emission Characteristics and Source Profiles
The 47 VOC species were classified into four groups, including 26 alkanes, 10 alkenes, 10 aromatics, and 1 alkyne. As this study focused on the VOC source profile of a typical coal utilization process, the mass fraction of the 47 VOC species was calculated to investigate the VOC emission characteristics of typical coal utilization sources. The mass fractions of the 47 VOC species emissions from each coal utilization source are presented in Fig. 1, and the VOC group weight percentages from emission sources are shown in Fig. 2.

3.1.1 Power plant
The main VOC species in the flue gas of power plants were 1-butene, propane, isobutane, acetylene, toluene, and styrene. 1-Butene was the largest contributing VOC species of Power

![Fig. 1. VOC source profiles of coking plant, steel plants, power plants and residential stoves.](image1)

![Fig. 2. VOC group weight percentages from different emission sources.](image2)
with the SPECIATE 5.1 data, we measured more alkenes and fewer aromatics in the coal-fired burnig boiler electric generation, followed by alkanes (23.4%) and alkenes (11.8%). In comparison et al. et al. et al. source profile of power plants suggests that the VOC emission characteristics were largely affected by both coal utilization technology and coal quality. Our VOC al. al. al. fractions of benzene in Power Plants A and B were less than 1.0%, which were lower than those of Power Plants C, D, and E (6.4%, 2.1%, and 2.5%, respectively). The same situation was also observed for toluene, with toluene percentages of 0.5% and 1.4% for Power Plant A and B, respectively, and 16.0%, 5.6%, and 5.5% for Power Plants C, D, and E, respectively.

The major VOC groups of the three power plants with pulverized coal-fired boilers (A, B, and C) were alkenes and aromatics, accounting for 89.7%, 79.9%, and 71.0%, respectively. The main VOC groups of the two power plants with a circulating fluidized bed boiler (C and D) were alkenes and alkanes, in total accounting for 82.1% and 73.4%, respectively. Alkyn from the three pulverized coal-fired boiler power plants were all less than 1%, while those of two circulating fluidized bed boiler power plants were 11.6% and 3.4%, respectively. According to SPECIATE 5.1 (U.S. EPA, 2020), aromatics were the main VOC group (64.8%) from the stack flue gas of coal-burning boiler electric generation, followed by alkanes (23.4%) and alkenes (11.8%). In comparison with the SPECIATE 5.1 data, we measured more alkenes and fewer aromatics in the coal-fired power plants in this study. In contrast, previous studies identified aromatics (Shi et al., 2015; Yan et al., 2016; Li et al., 2018) to be the largest VOC group in China. Therefore, these variations were likely caused by regional differences in coal combustion technology and coal quality. Our VOC source profile of power plants suggests that the VOC emission characteristics were largely affected by both coal utilization technology and coal sources.

3.1.2 Steel plant

The main VOC species in the flue gas of blast furnace ironmaking were 2-methylpentane, 2,3-dimethylbutane, cyclopentane, 1-butene, and toluene, while the main VOC species in the sintering process were ethane, benzene, propylene, 1-butene, and propane. Benzene and toluene were also found to be the main species in the ironmaking process in Liaoning (Shi et al., 2015) and Taiwan (Tsai et al., 2008) steel plants, as shown in Fig. S2 and Table S2. The largest VOC species from the ironmaking process was 2-methylpentane, accounting for 26.5%, but this species was not detected in the ironmaking process in Liaoning (Shi et al., 2015). As for the sintering process, the weight fraction of benzene was 14.4%, which is consistent with the weight fraction of 16.1% reported by Miao (2017). Propylene (10.2%), 1-butene (7.2%), toluene (6.1%), propane (5.4%), ethylene (5.3%), and n-butane (3.5%) were the main species in the flue gas during sintering process. Among these species, benzene, 1-butene, n-butane, and toluene were also the most abundant species in the sintering process of Taiwan steel plants (Tsai et al., 2008). Notably, ethane was the largest VOC species in the flue gas of the sintering process in this study. According to SPECIATE 5.1 (U.S. EPA, 2020), ethane was also the major compound in the iron sintering process but was not detected in some steel plant studies (Tsai et al., 2008; Shi et al., 2015; Miao, 2017). Alkane was the most abundant VOC group emitted from both the blast furnace ironmaking process and sintering process, accounting for 69.5% and 48.9%, respectively (Fig. 2). Previous studies identified aromatics to be the largest VOC group in Taiwan and Liaoning (Tsai et al., 2008; Shi et al., 2015). The weight fractions of aromatics, alkenes, and alkynes in the blast furnace ironmaking process were 17.3%, 13.1%, and 0.1%, respectively, and in the sintering process were 26.8%,
22.1%, and 2.2%, respectively (Fig. 2). The different combustion technologies, combustion temperature, burning materials, and VOC source profiles in this study suggest that the emission characteristics of VOCs differed between the two coal utilization processes of steel plants.

3.1.3 Coking plant

The main VOC species from the coking plant were benzene, styrene, ethylene, ethane, and propane. Benzene was the largest VOC species contributor, contributing 32.1% to the total VOCs. As shown in Fig. S3 and Table S3, styrene was the main VOC species in the coking plant in this study (mass fraction of 35.6%), which is contradictory to previous findings of similar studies that determined styrene mass fractions of less than 1% (Jia et al., 2009; Shi et al., 2015; Wang et al., 2017; Li et al., 2018). Benzene was also the main VOC species in the coking plant, with a weight fraction of 17.6%, and was also the main species (with a weight fraction of 20.5%) in Hebei (19.1%), alkenes (14.1%), and alkynes (0.9%).

The weight fraction of ethene was 9.6% and was identified as the main VOC emission species from coking plants in other studies (Jia et al., 2009; Shi et al., 2015; Wang et al., 2017), the percentage of benzene was much lower than in this study, with 8.1% reported by Shi et al. (2015), 4.5% reported by Wang et al. (2017), and 0.2% and 0.4% reported by Jia et al. (2009). The weight fraction of ethene was only 3.4% in this study and less than 0.1% in Liaoning Province (Shi et al., 2018), but its value in other studies ranged from 18.5% to 28.9% (Jia et al., 2009; Wang et al., 2017; Li et al., 2018). The VOC characteristics in coking plants showed large differences between different regions due to the different coke oven models, materials, and coking temperatures applied. Among the species, aromatics were the largest contributors (66.4%), followed by alkanes (19.1%), alkenes (14.1%), and alkynes (0.9%).

3.1.4 Residential stove

In this study, 1-butene was the largest contributor to the total VOC emissions from residential coal-burning stoves, accounting for 44.9%. 1-Butene was also the main VOC species identified in three different types of coal (raw anthracite, raw bituminous coal, and briquette of bituminous coal) (Liu et al., 2008a). The second-largest species in the stack gas of residential stoves was ethylene, accounting for 12.5%, which was consistent with the results of other residential coal utilization studies, including 12.6% from Liu et al. (2008a) and 14.4% from Liu et al. (2017). As shown in Fig. S4 and Table S4, a higher weight fraction of ethylene was also found in many previous residential coal usage studies (Tsai et al., 2003; Wang et al., 2013; Mo et al., 2016). In addition, the abundant VOC species of residential coal usage included styrene (12.6%), 2,2-dimethyl butane (5.5%), propylene (4.5%), acetylene (2.5%), n-pentane (2.5%), ethane (2.3%), and benzene (1.9%). Among these species, ethane, acetylene, propylene, and benzene have also been observed as the dominant species in many similar studies (Tsai et al., 2003; Liu et al., 2008a; Wang et al., 2013; Mo et al., 2016; Liu et al., 2017). Alkenes were the major VOC group in the flue gas of residential coal-burning stoves, followed by aromatics, alkanes, and alkynes; accounting for 60.1%, 19.5%, 17.9%, and 2.5%, respectively. Some previous studies also found alkenes to be the most abundant VOC group in residential coal usage (Wang et al., 2013; Mo et al., 2016), while Liu et al. (2017) found alkynes to be the largest VOC group in residential coal usage, regardless of smoldering or flaming combustion processes. The results from Taiwan also showed that alkenes were the largest VOC group from residential coal usage (Tsai et al., 2003).

3.2 BTEX Ratio

The ratios of two particular VOC species of benzene series (benzene, toluene, ethylbenzene, and xylene) have been widely used to investigate the emission characteristics of VOCs. In a previous study, B/T ratios higher than 1 were considered to be associated with coal-fired industrial emissions (Santos et al., 2004; Liu et al., 2008a). As shown in Table 2, the average B/T ratios in this study varied greatly in different coal utilization processes. The B/T ratios in the power plant, sintering process of the steel plant, ironmaking process of the steel plant, coking plant, and residential stove were 0.47, 2.34, 0.56, 7.03, and 2.99, respectively.

The B/T ratios of five power plants ranged from 0.37 to 0.57, which are higher than those of coal-fired power stations in Liaoning Province (Shi et al., 2015) and lower than those of power
Table 2. BTEX ratios from different VOC emission sources.

| Source        | Reference                  | B:T | B:E | B:X | T:E | T:X | E:X | Notes                      |
|---------------|----------------------------|-----|-----|-----|-----|-----|-----|----------------------------|
| Power plants  | Power Plant A (this study) | 0.57| 0.16| 0.08| 0.29| 0.14| 0.49| Pulverized coal-fired boiler|
|               | Power Plant B              | 0.57| 0.31| 0.11| 0.55| 0.20| 0.36| Pulverized coal-fired boiler|
|               | Power Plant C              | 0.40| 2.43| 0.68| 6.09| 1.70| 0.28| Pulverized coal-fired boiler|
|               | Power Plant D              | 0.37| 2.14| 0.60| 5.84| 1.64| 0.28| Circulating fluidized bed boiler|
|               | Power Plant E              | 0.45| 2.36| 0.61| 5.20| 1.34| 0.26| Circulating fluidized bed boiler|
|               | Pudasainee et al. (2010)   | 1.73|     |     |     |     |     | Anthracite coal             |
|               | Santos et al. (2004)       | 8.53| 33.06| 55.71| 3.88| 6.53| 1.69| Bituminous coal             |
|               | Shi et al. (2015)          | 0.17| 2.75| 1.20| 15.80| 6.88| 0.44| Pulverized coal-fired boiler|
|               | Yan et al. (2016)          | 1.02| 0.19| 0.11| 0.19| 0.11| 0.58| Anthracite coal             |
|               | Li et al. (2018)           | 2.84| 5.16| 3.30| 1.81| 1.16| 0.64| Sintering                   |
| Steel plants  | This study                 | 2.34| 60.53| 12.83| 25.90| 5.49| 0.21| Sintering                   |
|               | Tsai et al. (2008)         | 0.56| 3.61| 0.86| 6.47| 1.54| 0.24| Ironmaking process          |
|               | Miao (2017)                | 3.61| 12.15| 5.77| 3.37| 1.60| 0.48| Sintering                   |
|               | Shi et al. (2015)          | 0.16| 3.29| 1.37| 20.56| 8.59| 0.42| Sintering                   |
| Coking plants | This study                 | 7.03| 7.17| 3.29| 1.02| 0.47| 0.46| Machine coke oven           |
|               | He et al. (2005)           | 0.22| 1.73| 0.32| 8.01| 1.45| 5.46| Traditional coke oven       |
|               | Tsai et al. (2008)         | 0.48| 4.18| 1.22| 8.65| 2.53| 3.41| Machine coke oven           |
|               | Jia et al. (2009)          | 1.27| 5.00| 0.79| 3.93| 0.62| 0.16| S8-II type                 |
|               | Shi et al. (2015)          | 1.28| 15.95| 1.75| 12.42| 1.36| 0.11| JN43-80 type                |
|               | Li et al. (2018)           | 3.06| 68.33| 9.76| 22.33| 3.19| 0.14| Cokemaking                 |
|               | Wang et al. (2017)         | 1.28| 9.49| 1.26| 7.40| 0.99| 0.13|                           |
| Residential   | This study                 | 2.99| 1.48| 0.92| 0.50| 0.31| 0.62|                           |
| stove         | Wang et al. (2013)         | 2.86|     |     |     |     |     | Raw anthracite              |
|               | Liu et al. (2008)          | 2.07| 5.68|     | 2.74|     |     | Smoldering combustion       |
|               | Liu et al. (2017)          | 1.13| 3.72|     | 3.29|     |     | Flaming combustion          |
|               | Mo et al. (2016)           | 3.47| 13.57| 6.25| 3.91| 1.80| 0.46|                           |
|               | Tsai et al. (2003)         | 1.99| 16.48| 2.17| 8.26| 1.09| 0.13|                           |
According to previous studies that assessed B/T ratios (Suthawaree et al., 2012), the B/T value can be used to distinguish traffic and non-traffic sources, with B/T ratios of approximately 0.5 regarded as traffic sources. However, in this study, the B/T ratios of the five power plants and ironmaking processes in steel plant blast furnaces were both approximately 0.5, and the B/T ratio of the coke oven in He et al. (2005) was 0.48. Therefore, the use of the B/T ratio to identify vehicular emission sources may not be sufficient.

3.3 OFP and SOA

As VOCs are the main precursors of ozone formation and SOAs, we analyzed the OFP and SOA formation potential of selected VOC species to investigate the influence of typical coal utilization processes on atmospheric ozone (Yao et al., 2006; Liu et al., 2008a).

3.3.1 OFP

The major ozone-forming species in the power plants was 1-butene, contributing approximately 67.2% to the ozone formation. Alkenes and aromatics were the main contributors to ozone formation in this study, accounting for 72.6% and 20.0%, respectively; they were also identified as major OFP VOC species in coal-burning power plants in previous studies (Shi et al., 2015; Yan et al., 2016). Among the five power plants, the OFP results differed between power plants with different coal utilization technologies. According to Fig. 3, no alkanes or alkynes were observed in the top 10 OFPs of VOC species in all three coal-fired power plants with pulverized coal-fired boilers, while 2-methylpentane and cyclopentane were the main OFP VOC species in both power plants that use circulating fluidized beds. In coking plants, the two most abundant oxygen-forming species were ethylene and styrene, contributing 46.2% to the total ozone formation. Although ethylene only accounted for 9.6% of the total VOC emissions from coking plants, the OFP of ethylene contributed 27.0% to ozone formation. In comparison, the OFP of alkenes and aromatics accounted for 37.2% and 47.0%, respectively. No alkanes or alkynes were observed in the top 10 OFPs of VOC species in the coking plant. As for steel plants, propylene, 1-butene, toluene, cis-2-butene, and m-xylene were the main species contributing to the OFP in both the blast furnace ironmaking process and the sintering process. Notably, although alkenes accounted for only 22.8% and 9.9% of the total VOC emissions from the blast furnace ironmaking process in

![Graph](https://example.com/graph.png)

**Fig. 3.** Contribution of VOC groups and the top 10 VOC species to the OFP in coking plants, steel plants, power plants, and residential stoves.
Table 3. Weight percentages of SOA formation for VOC species.

| VOC species       | FAC (%) | CONTRIBUTION RATE (%) | Plant A | Plant B | Plant C | Plant D | Plant E | Sintering furnace | Blast furnace | Coking plant | Residential usage |
|-------------------|---------|-----------------------|---------|---------|---------|---------|---------|------------------|---------------|--------------|------------------|
| Isoprene          | 2       |                       | 0.23    | 0.54    | 0.02    | 0.12    | 0.20    | 0.12             | 0.03          | 0.98         | 0.84             |
| Methylcyclopentane| 0.17    |                       | 0.05    | 0.04    | 0.03    | 0.09    | 0.13    | 0.11             | 0.18          | 0.03         | 0.06             |
| Cyclohexane       | 0.17    |                       | 0.19    | 0.29    | 0.02    | 0.08    | 0.12    | 0.15             | 0.18          | 0.17         | 0.07             |
| n-Heptane         | 0.06    |                       | 0.06    | 0.03    | 0.02    | 0.08    | 0.12    | 0.02             | 0.09          | 0.12         | 0.22             |
| Methylcyclohexane | 2.7     |                       | 0.46    | 0.51    | 0.91    | 2.01    | 3.20    | 1.69             | 3.57          | 0.22         | 0.25             |
| 2-Methylheptane   | 0.5     |                       | 0.14    | 0.13    | 0.12    | 0.35    | 0.51    | 0.04             | 0.30          | 0.03         | 0.04             |
| 3-Methylheptane   | 0.5     |                       | 0.12    | 0.11    | 0.09    | 0.31    | 0.52    | 0.07             | 0.35          | 0.03         | 0.05             |
| n-Octane          | 0.06    |                       | 0.04    | 0.04    | 0.02    | 0.04    | 0.07    | 0.01             | 0.04          | 0.01         | 0.06             |
| n-Nonane          | 1.5     |                       | 3.22    | 3.14    | 0.62    | 1.08    | 0.81    | 0.09             | 0.65          | 0.80         | 2.25             |
| Benzene           | 2       |                       | 1.31    | 1.77    | 7.50    | 6.79    | 8.09    | 40.63            | 10.22         | 36.50        | 13.30            |
| Toluene           | 5.4     |                       | 6.18    | 8.43    | 50.84   | 50.03   | 48.11   | 47.33            | 49.43         | 14.02        | 12.00            |
| Ethylbenzene      | 5.4     |                       | 21.52   | 15.28   | 8.34    | 8.57    | 9.24    | 1.83             | 7.64          | 13.74        | 24.23            |
| m-Xylene          | 4.7     |                       | 16.56   | 15.88   | 15.07   | 14.57   | 13.65   | 5.38             | 15.89         | 15.59        | 20.54            |
| p-Xylene          | 1.6     |                       | 2.59    | 2.73    | 1.80    | 2.35    | 3.93    | 0.42             | 2.42          | 0.78         | 0.80             |
| o-Xylene          | 5       |                       | 14.72   | 13.65   | 6.11    | 5.35    | 6.40    | 0.94             | 5.16          | 8.75         | 11.92            |
| 1,3,5-Trimethylbenzene | 2.9   |                       | 9.69    | 10.63   | 1.31    | 1.44    | 1.07    | 0.19             | 0.84          | 2.18         | 3.65             |
| 1,2,4-Trimethylbenzene | 2      |                       | 8.02    | 9.37    | 2.99    | 2.90    | 1.48    | 0.25             | 1.34          | 2.84         | 5.13             |
| 1,2,3-Trimethylbenzene | 3.6   |                       | 14.91   | 17.42   | 4.17    | 3.84    | 2.35    | 0.39             | 1.67          | 3.20         | 4.57             |

Steel plants, the OFP of alkenes in the top 10 VOC species contributed 76.0% and 37.2% to ozone formation in the two processes. In contrast, the alkane contribution rate to VOC emissions from the two steel plant processes was 41.0% and 55.3%, respectively, while the contribution of alkenes to ozone formation declined to 2.3% and 25.4%, respectively. This suggests that the chemical reactivity of alkenes during ozone formation is much higher than that of aromatics. Aromatics from steel plants contributed 11.7% and 18.6% to the OFP in the two processes, respectively. The main contributing species to the OFP in residential coal usage were 1-butene, ethylene, and propylene, accounting for 61.0%, 16.9%, and 7.9%, respectively. Moreover, alkenes had the highest contribution rate to ozone formation at 68.7%, followed by aromatics (8.0%) and alkanes (1.0%).

The contribution of different VOC species to ozone formation was influenced by both their concentration mass fractions and their maximum incremental reactivity coefficient value. Low-concentration mass fraction VOC species may have a high contribution rate to ozone formation; therefore, both high-concentration mass fractions and high-OFP VOC species should be considered for the effective control of VOC pollution. Our results showed that alkenes were the dominant oxygen-forming VOC group in the four types of coal utilization processes, and aromatics were the major ozone-forming VOC group in coal-fired steel plants and power plants. Alkenes were the largest contributor to the OFP in all five power plants, with an alkene percentage of more than 50%, and the major VOC species were similar among power plants. To improve the effectiveness of ambient ozone control measures, policymakers should focus more on alkenes and aromatics when establishing related policies for controlling VOCs.

3.3.2 SOA

VOCs also chemically react with atmospheric oxidants (OH, NOx, and O3) in the atmosphere, and the oxidation products subsequently form SOA, which influences atmospheric visibility. The potential formation of SOA in this study was estimated using fractional aerosol coefficients (Grosjean, 1992). According to Table 3, the top 5 VOC species contributing to the total SOA formation in the flue gases of coal utilization processes are all in the benzene series. In the four types of coal utilization processes, aromatics accounted for more than 94.0% of the total SOA formation. n-Nonane was the major VOC species contributing to SOA formation from power plants and residential stoves, and methylcyclohexane was the major VOC species of SOA formation from power plants and steel plants.
4 CONCLUSION

We evaluated the emission characteristics, OFP-related chemical reactivity, and SOA formation potential of VOCs originating from four types of coal-utilizing sources in northern China, namely, steel plants, power plants, coking plants, and residential stoves. The VOC profiles significantly varied between different coal utilization processes. Both the coal source and the combustion technology influenced the profiles for the five studied power plants. However, based on the BTEX ratios, the former factor played a larger role in shaping the BTEX emissions. Furthermore, at the steel plants, sintering generated alkanes and alkenes as the predominant VOC species (48.9% and 26.8% of the total VOCs, respectively), but blast furnace ironmaking generated alkanes and aromatics (69.5% and 17.3%). We also found far higher B/T ratios for power plants (0.37–0.57) than the one commonly recognized (1.0). As we collected all of our samples from Shanxi Province, subsequent research should assess whether these values are location-specific.

Additionally, we identified the largest contributors to the OFP of the emitted VOCs as alkenes for the steel plants, power plants, and residential stoves (59.0–87.6%) but as aromatics for the coking plants (55.8%). Notably, alkenes accounted for 33.6% of the total OFP at the steel plants (ironmaking process) but only 0–8.4% for the other sources. Lastly, above 94.0% of the SOA formation was attributable to aromatics across all of the studied sources.

ACKNOWLEDGMENTS

This work was supported by grants from the National Key R&D Program of China (No. 2019YFC0214200), the National Natural Science Foundation of China (NSFC; No. 21976053), the Fundamental Research Funds for the Central Universities (Nos. 2019QN089 and 2018ZD12), Key Project of Heavy Air Pollution Cause and Control (No. DQGG-05-13) and Hunan Provincial Key Research and Development Program (2018SK2039).

DISCLAIMER

The authors declare no competing financial interests.

SUPPLEMENTARY MATERIAL

Supplementary material for this article can be found in the online version at https://doi.org/10.4209/aaqr.210050

REFERENCES

Carter, W.P.L (2010). Updated maximum incremental reactivity scale and hydrocarbon bin reactivities for regulatory applications. California Air Resources Board Contract 07-339. Cetin, E., Odabasi, M., Seyfioglu, R. (2003). Ambient volatile organic compound (VOC) concentrations around a petrochemical complex and a petroleum refinery. Sci. Total Environ. 312, 103–112. https://doi.org/10.1016/S0048-9697(03)00197-9
Chen, C.L., Fang, H.Y., Shu, C.M. (2006). Mapping and profile of emission sources for airborne volatile organic compounds from process regions at a petrochemical plant in Kaohsiung, Taiwan. J. Air Waste Manage. Assoc. 56, 824–833. https://doi.org/10.1080/10473289.2006.10464486
Cheng, C.H., Su, L.Y., Wang, H.L., Huang, C., Li, L., Zhou, M., Qiao, Y.Z., Chen, Y.R., Chen, M.H., Huang, H.Y., Zhang, G.F. (2012). Variation and key reactive species of ambient VOCs in the urban area of Shanghai, China. Acta Sci. Circumst. 32, 367–376. https://doi.org/10.13671/j.hjkxxb.2012.02.022
China Coking Industry Association (2019). Forty years of development of coking industry reform
and opening up in China. China Coking Industry Association, China.
China Electricity Council (2020). China Electric Power Yearbook 2020, China Statistics Press, China.
Dagaut, P., Cathonnet, M. (1998). A comparative study of the kinetics of benzene formation from unsaturated C₂ to C₄ hydrocarbons. Combust. Flame 113, 620–623. https://doi.org/10.1016/s0010-2180(97)00244-7
Dai, L. (2017). The perennity of implementation of coal control strategy. Energy Conservation and Environmental Protection, 29–30. https://doi.org/10.27496/SUN.BJN.2017.01-013
 EVTyyagina, M., Calvo, A.I., Nunes, T., Alves, C., Fernandes, A.P., Tarelho, L., Vicente, A., Pio, C. (2013). VOC emissions of smouldering combustion from Mediterranean wildfires in central Portugal. Atmos. Environ. 64, 339–348. https://doi.org/10.1016/j.atmosenv.2012.10.001
 Fernández-Martínez, G., López-Mahía, P., Muniategui-Lorenzo, S., Prada-Rodríguez, D., Fernández-Fernández, E. (2001). Distribution of volatile organic compounds during the combustion process in coal-fired power stations. Atmos. Environ. 35, 5823–5831. https://doi.org/10.1016/s1352-2310(01)00242-5
Grosjean, D. (1992). In situ organic aerosol formation during a smog episode: Estimated production and chemical functionality. Atmos. Environ. 26, 953–963. https://doi.org/10.1016/0960-1686(92)80078-K
He, Q.S., Wang, X.M., Zhao, L.R., Sheng, G.Y., Fu, J.M. (2005). Preliminary study on profiles of VOCs emitted from coking. Environ. Monit. China 21, 61–65. https://doi.org/10.3969/j.issn.1002-6002.2005.01.019 (in Chinese)
Hu, X. (2017). Analysis on the Emission Characteristics and Control Technologies Application of Volatile Organic Compounds from Industries in Qinhuangdao. Tianjin University.
 Huang, H., Sha, Q., Zhu, M., Wang, Y., Lu, M., Zhanfg, X., Mingshuang, T., Zhijiong, H., Shi, B., Bai, L., Huang, J., Yan, M., Zheng, J. (2020). Evolution of emission characteristics and species of industrial VOCs emission in Pearl River Delta Region, 2010~2017. China Environ. Sci. 40, 4–14. https://doi.org/10.19674/j.cnki.issn1000-6923.20200915.001 (in Chinese)
James, J.S., Michael, J.K., Glen, R.C., Bernd, R.T.S. (2001). Measurement of emissions from air pollution sources. 3. C₁–C₉ organic compounds from fireplace combustion of wood fuel. Environ. Sci. Technol. 35, 1716–1728. https://doi.org/10.1021/es001331e
Jia, J.H., Huang, C., Chen, C.H., Chen, M.H., Wang, L.H., Shao, M., Dong, Y.L., Dai, P., Xie, S.C., Lu, J., Huang, H.Y. (2009). Emission characterization and ambient chemical reactivity of volatile organic compounds (VOCs) from coking processes. Acta Sci. Circumst. 29, 905–912. https://doi.org/10.13671/j.cnki.xxhjb.2009.05.030 (in Chinese)
Jumpponen, M., Roenkoemaaeki, H., Pasanen, P., Laitinen, J. (2013). Occupational exposure to gases, polycyclic aromatic hydrocarbons and volatile organic compounds in biomass-fired power plants. Chemosphere 90, 1289–1293. https://doi.org/10.1016/j.chemosphere.2012.10.001
 Kawashima, H., Minami, S., Hanai, Y., Fushimi, A. (2006). Volatile organic compound emission factors from roadside measurements. Atmos. Environ. 40, 2301–2312. https://doi.org/10.1016/j.atmosenv.2005.11.044
 Li, G.H., Wei, W., Cheng, S.Y., Wen, W., Wang, G. (2014). Emission characterization and ozone formation potential of VOCs during the coking process. J. Beijing Univ. Technol. 40, 91–99. https://doi.org/10.254-0037(2014)01-0091-09 (in Chinese)
 Li, G.H., Wei, W., Shao, X., Nie, L., Wang, H.L., Yan, X., Zhang, R. (2018). A comprehensive classification method for VOC emission sources to tackle air pollution based on VOC species reactivity and emission amounts. J. Environ. Sci. 67, 78–88. https://doi.org/10.1016/j.jes.2017.08.003
 Lin, T.Y., Sree, U., Tseng, S.H., Kong, H.C., Wu, C.H., Lo, J.G. (2004). Volatile organic compound concentrations in ambient air of Kaohsiung petroleum refinery in Taiwan. Atmos. Environ. 38, 4111–4122. https://doi.org/10.1016/j.atmosenv.2004.04.025
 Liu, C.T., Zhang, C.L., Mu, J.Y., Liu, J.F., Zhang, Y.Y. (2017). Emission of volatile organic compounds from domestic coal stove with the actual alternation of flaming and smoldering combustion processes. Environ. Pollut. 221, 385–391. https://doi.org/10.1016/j.envpol.2016.11.089
 Liu, Y., Shao, M., Fu, L., Lu, S., Zeng, L., Tang, D. (2008a). Source profiles of volatile organic compounds (VOCs) measured in China: Part I. Atmos. Environ. 42, 6247–6260. https://doi.org/10.1016/j.atmosenv.2008.01.070
 Liu, Y., Shao, M., Lu, S., Chang, C.C., Wang, J.L., Fu, L. (2008b). Source apportionment of ambient
volatile organic compounds in the Pearl River Delta, China: Part II. Atmos. Environ. 42, 6261–6274. https://doi.org/10.1016/j.atmosenv.2008.02.027

Lv, Z.F., Hao, J.M., Chun, D.J., Li, J.H. (2009). Estimate of the formation potential of secondary organic aerosol in Beijing summertime. Environ. Sci. 30, 969–975. (in Chinese)

Ma, Z.Z., Li, Z., Jiang, J.K., Ye, Z.X., Deng, J.G., Duan, L. (2015). Characteristics of water-soluble inorganic ions in PM2.5 emitted from coal fired power plants. Environ. Sci. 36, 2361–2366. https://doi.org/10.13227/j.jhjkx.2015.03.047 (in Chinese)

Miao, P.R. (2017). Research on VOCs emission characteristics in sintering process. Environ. Dev. 29, 79–86. https://doi.org/10.1016/j.cnki.cn15-1369/X.2017.02.015 (in Chinese)

Ministry of Ecological Environment (2020). State of the environment bulletin of China 2019. Ministry of Ecological Environment, China.

Mo, Z., Shao, M., Lu, S.H. (2014). Emission characteristics of volatile organic compounds (VOCs) from typical solvent use factories in Beijing, China. Acta Sci. Circumst. 34, 2179–2189. https://doi.org/10.1111/j.1600-0609.2007.00986.x (in Chinese)

Mo, Z., Lu, S.H., Li, Y., Shao, M., Qu, H. (2015). Emission characteristics of volatile organic compounds (VOCs) from typical solvent use factories in Beijing. China Environ. Sci. 35, 374–380. (in Chinese)

Mo, Z., Shao, M., Lu, S. (2016). Compilation of a source profile database for hydrocarbon and OVOC emissions in China. Atmos. Environ. 143, 209–217. https://doi.org/10.1016/j.atmosenv.2016.08.025

National Bureau of Statistics (2019). China Energy Statistics Yearbook 2019. China Statistical Press, China.

Niedojadlo, A., Becker, K.H., Kurtenbach, R., Wiesen, P. (2007). The contribution of traffic and solvent use to the total NMVOC emission in a German city derived from measurements and CMB modelling. Atmos. Environ. 41, 7108–7126. https://doi.org/10.1016/j.atmosenv.2007.04.056

Olson, D.A., Hammond, D.M., Seila, R.L., Burke, J.M., Norris, G.A. (2009). Spatial gradients and source apportionment of volatile organic compounds near roadways. Atmos. Environ. 43, 5647–5653. https://doi.org/10.1016/j.atmosenv.2009.07.065

Pudasainee, D., Kim, J.H., Lee, S.H., Park, J.M., Jang, H.N., Song, G.J., Seo, Y.C. (2010). Hazardous air pollutants emission from coal and oil-fired power plants. Asia-Pac. J. Chem. Eng. 5, 299–303. https://doi.org/10.1002/apj.268

Santos, M.C.Y., Azevedo, A.D., Neto, A.F.R. (2004). Atmospheric distribution of organic compounds from urban areas near a coal-fired power station. Atmos. Environ. 38, 1247–1257. https://doi.org/10.1016/j.atmosenv.2003.11.026

Shi, J., Deng, H., Bai, Z., Kong, S., Wang, X., Hao, J., Han, X., Ning, P. (2015). Emission and profile characteristic of volatile organic compounds emitted from coke production, iron smelt, heating station and power plant in Liaoning Province, China. Sci. Total Environ. 515–516, 101–108. https://doi.org/10.1016/j.scitotenv.2015.02.034

Suthawaree, J., Tajima, Y., Khunchornyakong, A., Kato, S., Sharp, A., Kajii, Y. (2012). Identification of volatile organic compounds in suburban Bangkok, Thailand and their potential for ozone formation. Atmos. Res. 104–105, 245–254. https://doi.org/10.1016/j.atmosres.2011.10.019

Tian, L. (2015). Research on VOCs Emission Characteristics and Ozone Generation Potential of Typical Industries in Beijing. Environmental Science and Engineering Beijing University of Technology, China.

Tsai, J.H., Lin, K.H., Chen, C.Y., Lai, N., Ma, S.Y., Chiang, H.L. (2008). Volatile organic compound constituents from an integrated iron and steel facility. J. Hazard. Mater. 157, 569–578. https://doi.org/10.1016/j.jhazmat.2008.01.022

Tsai, S.M., Zhang, J.J., Smith, K.R., Ma, Y., Rasmussen, R.A., Khalil, M.A.K. (2003). Characterization of non-methane hydrocarbons emitted from various cookstoves used in China. Environ. Sci. Technol. 37, 2869–2877. https://doi.org/10.1021/es026232a (in Chinese)

U.S. Environmental Protection Agency (U.S. EPA) (2020). SPECIATE 5.1. U.S. Environmental Protection Agency. https://www.epa.gov/air-emissions-modeling/speciate-4

Wang, D.S., Wang, M.R., Bai, X.F., Ding, H. (2016). The situation analysis of civil coal in the Beijing-Tianjin-Hebei region. Coal Qual. Technol. 46–49. https://doi.org/10.3969/j.issn.1007-7677.2016.03.015 (in Chinese)
Wang, L.H., Yang, Z.X., Jing, S.A. (2017). Volatile organic compounds (VOCs) source profiles of industrial processing and solvent use emissions: A review. Environ. Sci. 38, 2617–2628. https://doi.org/10.13227/j.hjkx.201611119 (in Chinese)

Wang, Q., Geng, C., Lu, S., Chen, W., Shao, M. (2013). Emission factors of gaseous carbonaceous species from residential combustion of coal and crop residue briquettes. Front. Environ. Sci. Eng. 7, 66–76. https://doi.org/10.1007/s11783-012-0428-5

Wu, R., Xie, S. (2017). Spatial distribution of ozone formation in China derived from emissions of speciated volatile organic compounds. Environ. Sci. Technol. 51, 2574–2583. https://doi.org/10.1021/acs.est.6b03634

Yan, Y., Yang, C., Peng, L., Li, R., Bai, H. (2016). Emission characteristics of volatile organic compounds from coal-, coal gangue-, and biomass-fired power plants in China. Atmos. Environ. 143, 261–269. https://doi.org/10.1016/j.atmosenv.2016.08.052

Yao, L., Ge, M.F., Qiao, Z.M., Sun, Z., Wang, D.X. (2006). Progresses of tropospheric chemistry of volatile organic compounds. Chem. Online 69, 1–7.

Yao, S., Wei, W., Cheng, S.Y., Wang, G., Zhang, H.Y., Lei, C.G. (2016). Emission characteristics and chemical reactivity of volatile organic compounds from light-duty gasoline vehicles. China Environ. Sci. 36, 2923–2929. https://doi.org/10.3969/j.issn.1000-6923.2016.10.008 (in Chinese)

Yuan, B., Min, S., Lu, S., Wang, B. (2010). Source profiles of volatile organic compounds associated with solvent use in Beijing, China. Atmos. Environ. 44, 1919–1926. https://doi.org/10.1016/j.atmosenv.2010.02.014

Zhan, X. (2015). The Investigation on Chemical Compositions and Characteristics of Petrochemical Industrial VOCs Emission Sources in Tianjin City. University of Technology, China.

Zhang, J., Smith, K.R. (2007). Household air pollution from coal and biomass fuels in China: measurements, health impacts, and interventions. Environ. Health Perspect. 115, 848–855. https://doi.org/10.1289/ehp.9479

Zhang, Q.J., Wu, L., Liu, M.Y., fang, X.Z., Zhang, J., Mao, H.J., Shao, M., Lu, S.H. (2016). Pollution Characteristics And Health Risk Assessment Of Vocs From Vehicle Exhaust In Nanjing. China Environ. Sci. 36, 3118–3125. https://doi.org/CNKI:SUN:ZGHJ.0.2016-10-032 (in Chinese)

Zou, X.B., Zhou, X., Wu, Y.Q. (2013). Research progress of controlling volatile organic compounds in flue gas of coal-fired power plant. Environ. Sci. Surv. 32, 57–62. https://doi.org/10.3969/j.issn.1673-9655.2013.06.016 (in Chinese)