Journal of Environmental Sciences 26 (2014) 2–12

Available online at www.sciencedirect.com

Journal of Environmental Sciences

www.jesc.ac.cn

Haze insights and mitigation in China: An overview

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ARTICLE INFO

Article history:
Special issue: Progress and prospects of atmospheric environmental science in China

Keywords:
haze
secondary aerosols
size distribution
particles
chemical composition

DOI: 10.1016/S1001-0742(13)60376-9

ABSTRACT

The present article provides an overview of the chemical and physical features of haze in China, focusing on the relationship between haze and atmospheric fine particles, and the formation mechanism of haze. It also summarizes several of control technologies and strategies to mitigate the occurrence of haze. The development of instruments and the analysis of measurements of ambient particles and precursor concentrations have provided important information about haze formation. Indeed, the use of new instruments has greatly facilitated current haze research in China. Examples of insightful results include the relationship between fine particles and haze, the chemical compositions and sources of particles, the impacts of the aging process on haze formation, and the application of technologies that control the formation of haze. Based on these results, two relevant issues need to be addressed: understanding the relationship between haze and fine particles and understanding how to control $PM_{2.5}$.

Introduction

Haze is an atmospheric phenomenon that is characterized by visibility of less than 10 km due to complex material that is suspended in the air, such as dust, smoke and other fine particles. PM_{10}, $PM_{2.5}$ and PM_1 refer to particles smaller than 10, 2.5 and 1 μm in aerodynamic diameter, respectively. Particles with an aerodynamic diameter less than 2.5 μm are referred to as "fine particles" and are believed to pose greater health risks than larger particles because they can embed themselves deep within the lungs. In addition to the adverse health effects in humans, $PM_{2.5}$-induced urban and nonurban haze can change the radiation balance of the earth, damage forests and crops, and contaminate lakes and rivers.

Visible haze is related to nearly every pollutant in the air. In China, the public debate regarding $PM_{2.5}$ and PM_{10} began because the air quality monitoring results released by Beijing's Weather Forecasting Station and those released by the U.S. Embassy in Beijing often differed. While the embassy results described Beijing's air quality as "hazardous" or "dangerous", the Beijing Weather Forecasting Station would often classify the pollution as "minor". Both sources defended their stances by saying that the divergence resulted from the differences in measurement standards. China currently uses the amount of PM_{10}, or particulate matter with an aerodynamic diameter less than 10 μm, to measure air quality. The use of this

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measurement is often viewed as the root of discrepancies between the governmental ratings and the perceptions held by the Chinese citizens. In January 2012, Beijing finally announced that the air quality monitoring data for $PM_{2.5}$ would be released to the public (these data had previously only been available for laboratory use).

In past decades, the measurement of $PM_{2.5}$ has been implemented in many institutes of the Chinese Academy of Sciences (CAS), including the Institute of Atmospheric Physics (IAP), the Research Center of Eco-Environmental Sciences (RCEES), the Guangzhou Institute of Geochemistry (GIG), the Institute of Earth Environment (IEE), the Anhui Institute of Optics and Fine Mechanics (AIOFM), the Institute of Process Engineering (IPE), the Institute of Chemistry (IC), and the Institute of Urban Environment (IUE). Tremendous progress has been achieved in the equipment and technology used for $PM_{2.5}$ measurement, long-term data monitoring and analysis, understanding the mechanisms of $PM_{2.5}$ formation, and $PM_{2.5}$ exposure control. The present review describes the progress and the prospects of $PM_{2.5}$ research in China with a focus on the results from the CAS.

1 Formation mechanism of haze

1.1 Relationship between haze and fine particles

Haze is an atmospheric phenomenon in which fine particles contribute to light extinction through scattering and absorption, which obscure the clarity of the sky (Watson, 2002). For particles, the extinction coefficient is closely related to size, morphology, chemical composition and mixing state (Madronich and Flocke, 1999). Indeed, particles with diameters between 0.4 and 1.0 μm (optical equivalent diameter) have the highest extinction potential in the atmosphere (the wavelength of visible light is between 0.4 and 0.7 μm). Because fine particles are small and have low densities and high buoyancies, they survive for longer periods of time in the atmosphere (Haglera et al., 2006). Fine particles also act as carriers for heterogeneous chemical reactions (Pathak et al., 2009). Differential transmission within an air mass in the atmosphere results in complex and regional differences in haze.

Because single particle density can vary significantly, there is no quantitative relationship between particle mass concentration and visibility. Compared with mass concentration, the number concentration of fine particles per unit volume has a more direct impact on the formation of haze. The reduction in visibility is therefore primarily influenced by particle number concentration rather than particle mass concentration. Indeed, a larger particle number concentration indicates that more fine particles are participating in the scattering of visible light (Bäumer et al., 2008).

As observed by the IAP, $PM_{2.5}$ mass concentration accounted for 60% of PM_{10}, and the $PM_{1.0}$ mass concentration accounted for 60% of the $PM_{2.5}$ in Beijing (Liu et al., 2011a). Interestingly, the $PM_{2.5}$ number concentration that scattered visible light accounted for 99% of PM_{10}. Visibility in Beijing is very good when the fine particle ($PM_{0.4-1}$) number concentration is less than 1000 cm^{-3}, and light haze appears when the fine particle number concentration increases to 3500 cm^{-3}. When the number concentration of fine particles increases to more than 15,000 cm^{-3}, the visibility declines sharply because of wide-ranging regional haze pollution (Liu et al., 2011a).

1.2 Relationship between PM_{10}, $PM_{2.5}$ and PM_1

Although the national air quality standards of China only included guidelines for PM_{10} levels in the past, guidelines for $PM_{2.5}$ and PM_1 have recently been established (**Table 1**). Generally, PM_{10} refers to inhalable particles. Importantly, $PM_{2.5}$ can penetrate deep into the lungs, and PM_1 is a subset of inhalable $PM_{2.5}$ particles that can trigger the inflammation of blood vessels, the heart, and other organs. $PM_{2.5-10}$ is considered to be coarse particles and account for a large fraction of PM_{10}. However, there are few coarse particles per unit volume in the atmosphere, and coarse particles play only a minor role in atmospheric extinction. In recent years, the Beijing Municipal Government implemented a series of environmental measures, such as the relocation of the capital steel factory, banning diesel cars, and enclosing dusty and other construction sites, which have greatly reduced the concentrations of coarse particles. However, extinction-induced haze is attributed to $PM_{2.5}$, and $PM_{2.5}$ concentrations slightly increased during this time. These conflicting results gave rise to the opposing reports of acceptable PM_{10} concentrations by the Ministry for Environmental Protection, thus worsening public opin-

Table 1 National air quality standards of China

Species	Time range	Thresholds (mg/m^3)	
		Grade I	Grade II
TSP	Yearly	0.08	0.2
	Daily	0.12	0.3
PM_{10}	Yearly	0.04	0.07
	Daily	0.05	0.15
$PM_{2.5}$	Yearly	0.015	0.035
	Daily	0.035	0.075
SO_2	Yearly	0.02	0.06
	Daily	0.05	0.15
	Hourly	0.15	0.5
NO_2	Yearly	0.04	0.04
	Daily	0.08	0.08
	Hourly	0.20	0.20
CO	Daily	4	4
	Hourly	10	10
O_3	8-hr	0.10	0.16
	Hourly	0.16	0.20

ion of air quality.

1.3 Relationship between haze and the chemical compositions of $PM_{2.5}$

Most of the fine particles that are found in urban areas originate with the burning of fossil fuels, and most of these particles exhibit a porous structure and have very large specific surface areas. As a result, the fine particles have the ability to absorb toxic and harmful substances. Another important source of atmospheric $PM_{2.5}$ is the heterogeneous formation of new secondary particles using primary particles as carriers. The contribution of secondary particles can be as high as 20%–80% on a global scale and can reach up to 60% in the eastern part of China (Seinfeld and Pandis, 1998). For example, ultrafine $CaCO_3$ particles have a very weak light extinction effect, but after traveling from northwestern China to northern China, the $CaCO_3$ particles react with the acidic gases SO_2 and NOx, which are emitted near cities, to generate $CaSO_4$ and $Ca(NO_3)_2$. These compounds have strong hygroscopicity. Thus, the particles absorb water and expand, forming haze particulates with high light extinction abilities. Primary particles are produced and expanded through physical (absorption) and chemical processes (heterogeneous reaction) that involve nearly all of the elements in the periodic table. As a result, there are no fewer than thirty thousand compounds that can be formed and can lead to air pollution, which underscores the difficulty in understanding haze formation.

An analysis of the chemical composition of $PM_{2.5}$ by the IAP in the Beijing-Tianjin-Hebei (BTH) region revealed that secondary water-soluble ions included sulfate, nitrate and ammonium salts (30%–40%); carbonaceous aerosol (30%–40%); and metallic elements (approximately 10%). Taking gasoline quality as an example, the sulfur content of gasoline in China is relatively high compared with Europe and Japan. The sulfur in gasoline can produce nanometer-sized, ultrafine-particulate sulfate and nitrate (weak light extinction ability), which can then aggregate and grow into particles larger than 0.4 μm (strong light extinction ability) and form haze particles. In addition, the gasoline and diesel fuel in China is primarily produced by heavy oil schizolysis, which results in a very high olefin content. The burning of oil can easily form black carbon particles that directly absorb visible light. Although the density of black carbon particles is low (accounting for a small portion of the PM_{10} mass concentration), the burning of oil produces a large number of black carbon particles, which can lead to haze. In recent years, an increasing number of incidents of serious haze pollution have been closely related to the rapid increase of lightweight carbonaceous aerosols. This is another reason why the Environmental Protection Agency data vary from public opinion.

Based on long-term observations of $PM_{2.5}$ in the Pearl River Delta region (PRD), scientists from the GIG have investigated $PM_{2.5}$ exposure levels in typical microenvironments (Song et al., 2004; Li et al., 2011; Zhao et al., 2005; Wang et al., 2006a; Long et al., 2010) and the chemical composition and sources of $PM_{2.5}$ in ambient air (Wang et al., 2006b; Duan et al., 2007; Tan et al., 2009a, 2009b; Lv et al., 2010a, 2010b; Gao et al., 2011;Wei et al., 2011). They also compared the chemical compositions of $PM_{2.5}$ on hazy days with the concentrations during normal days (Li et al., 2011; Tan et al., 2009a, 2009b). The hemotoxic potencies of $PM_{2.5}$ and their different organic fractions during normal and hazy days were further investigated, and the results indicated that $PM_{2.5}$ pollution and the adverse health effects of haze appeared on a regional scale (Xu et al., 2008). Chemical extinction analysis revealed that organic matter contributed 28% to light extinction, which was close to that of sulfate (32%), and played a key role among all of the components that impaired visibility (Wang et al., 2012a).

Field observations in the PRD region have suggested that secondary organic aerosols (SOA) have a significant negative impact on atmospheric visibility (Tan et al., 2009a, 2009b). Tracer-based SOA estimations have demonstrated that SOA in the PRD region are predominately (approximately 75%) related to anthropogenic precursors such as aromatics (Ding et al., 2012). Among the biogenic SOA, acid-catalyzed heterogeneous reactions were found to be the major formation pathway of isoprene SOA tracers (e.g., 2-methyltetrols) in the PRD region. However, there was a huge gap in the influence of aerosol acidity on SOA tracer formation in the PRD region compared with previous chamber studies (i.e., 2 orders of magnitude lower). This result indicated that the SOA formation was more complex in the real atmosphere and that caution should be taken when extrapolating the chamber results to describe ambient samples (Ding et al., 2011).

Presently, the formation mechanisms and number of atmospheric fine particles, especially nanometer-sized particles, are not clear. The physical and chemical properties are complex, the spatial-temporal evolution is large, and elucidating the effect of nanometer particles on the formation of haze particles is a new challenge in atmospheric research.

1.4 Impact of aging on haze formation

Air pollution in China is characterized by the coexistence of high concentrations of gaseous pollutants and particulate matter in the atmosphere. As mentioned above, $PM_{2.5}$, especially PM_1, exists in the atmosphere for a long period of time and can be transported over long distances. In addition, many gaseous pollutants are readily adsorbed onto PM because of its large surface area. Thus, heterogeneous and multiphase reactions between gaseous pollutants and PM in the atmosphere not only change the distribution of gaseous pollutants but also greatly alter the chemical composition and the physicochemical properties of PM. This phenomenon is referred to as the aging of PM. Secondary aerosol formation due to the oxidation of gaseous precursors by photo-oxidants and simultaneous heterogeneous reactions are very important mechanisms of haze formation. Because of their uneven temporal and spatial distributions, the participation of numerous species and synergetic and antagonistic effects, the mechanisms of haze formation are very complicated. Thus, many atmospheric and environmental science studies have focused on investigating the mechanisms of haze formation.

Studies have shown that the reactions between atmospheric trace gases (e.g., NO_2, SO_2, OCS, and CH_3COOH) and mineral dust particles result in the formation of nitrate, sulfate, and acetate that become internally mixed with mineral particles (He et al., 2005; Liu et al., 2008b, 2012a; Liu and He, 2009; Ma et al., 2008; Tong et al., 2010). In addition, the oxidation of soot by O_3 can yield oxygenated polar species on the soot surface (Liu et al., 2010a). The internally mixed soluble salts or polar species can then enhance the hydrophilicity of the particles (Ma, 2010a). The high hygroscopicity of PM can further promote the reaction between PM and the soluble gaseous pollutants to increase particle size and enhance light extinction, both of which are conducive to the formation of haze.

The ICCAS carried out a series of laboratory investigations to study homogeneous reactions between VOCs and free radicals, such as OH, NO_3, and Cl. We discovered important short-lived, high-activity species, reaction pathways and mechanisms in the atmospheric chemical conversion processes. The results provided basic data and scientific support for studying the atmospheric chemistry of VOCs and for evaluating their environmental effects (Du et al., 2007; Wang et al., 2009, 2010a; Gai et al., 2009, 2011). Subsequently, we extended the study of heterogeneous kinetics to involve photo-oxidants, which highlighted the heterogeneous reactions between H_2O_2 and aerosols. It was demonstrated that multi-phase, acid-catalyzed oxidation by H_2O_2 might be an important source of secondary organic aerosols (Wang et al., 2011; Liu et al., 2011b, 2012b). In addition, environmental factors are very influential in heterogeneous mechanisms. Indeed, studies have shown that differences in relative humidity can lead to variations in the reactions between organic acids and dust (Tong et al., 2010), whereas low temperatures can increase heterogeneous reactions between SO_2 and dust (Wu et al., 2011). Studies of the formation and aging of secondary aerosols have created a solid foundation for tracing the causes of haze.

2 Instrument development and measurements

2.1 Observation techniques and instrument development

$PM_{2.5}$ monitoring requires continuous, real-time, online measurements of not only mass concentration but also the size, number, and composition of the particulate matter. Currently, both an atmospheric fine particle mass concentration ($PM_{2.5}$) automatic online monitor and a carbon black aerosol analyzer developed by the CAS have been industrialized. The aerodynamic particle size analyzer is able to achieve long-term unattended operation. In addition, an atmospheric organic carbon/elemental carbon analyzer has passed product authentication and has advanced to the development stage.

For online measurements of atmospheric fine particles ($PM_{2.5}$), several key techniques and elements have been developed. These key advances include a highly cost-effective and reliable mass-transmission unit (Lu et al., 2004), a very sensitive micro-vibration sensor that utilizes a hall element, and a suspended-type shockproof system for oscillating tubes (**Table 2**). High-precision, high-stability $PM_{2.5}$ measurements were finally achieved with tapered element oscillating microbalance technology

Table 2 Instrument development

	Observation parameters				
	$PM_{2.5}$	BC	Number concentration	EC/OC	Extinction
Instrument model	AGHJ-I-TEOM Particle Mass Concentration Online Monitor	BCA7 Black Carbon Aerosol Analyzer	APDS-II Aerosol Particle Diameter Spectrometer	HJGX-I OC/EC Online Monitor	–
Detection principle	Tapered element oscillating microbalance technology	Optical attenuation method	Time-of-flight of individual particles measured in an accelerating flow field	Thermal-optical method	Cavity ring-down spectroscopy technology
Detection limit	2 μg/m^3	0.2 μg/m^3	500 nm	EC: 0.2 μg C/cm^2 OC: 0.9 μg C/cm^2	0.2 (mol/(L·m))
Accuracy	± 2.0 μg/m^3 (1-hr average) ± 1.0 μg/m^3 (24-hr average)	± 5%	–	± 5%	± 3%
Measurement range	2 μg–5 mg/m^3	0.2–400 μg/m^3	500 nm–20 μm	0.2–750 μg C/cm^2	2×10^{-7}–10^{-2} m^{-1}
Response time	30 min	5 min	> 30 sec	30 min	< 10 sec
Others	Detection sensitivity: 0.1 μg/m^3	Detection sensitivity: 0.1 μg/m^3	52 channels concentration < 10^4 cm^{-3}	–	–

(Lu et al., 2007). These atmospheric fine particle concentration monitoring systems are already being employed for environmental monitoring, and the results meet the requirements for atmospheric fine particle measurement (Ding et al., 2009b).

For the online measurement of atmospheric particle size distribution, an aerosol size distribution analyzer was developed (**Table 2**). This instrument is based on the time-of-flight principle by utilizing an aerodynamic focusing nozzle, dual-port random access memory, the birefringence splitting technique and high-speed, large-capacity, multichannel storage (Huang et al., 2004, 2007, 2009; Lian et al., 2004; Zhu et al., 2010, 2011). These aerosol particle size analyzers can measure the number of atmospheric particles with sizes ranging from 0.5 to 10 microns with the advantages of continuous, real-time, online measurement (Huang et al., 2010). The main technical specifications of these instruments have reached levels similar to those of instruments employed in the United States.

For the online measurement of the concentration of black carbon (BC), multi-wavelength absorption measurement techniques have been investigated. By integrating double optical paths (Wu et al., 2007a), a multiwavelength light source array, a multichannel weak signal acquisition system, and a BC aerosol analyzer was successfully developed (**Table 2**). As a result, BC concentrations in the range of 0.1–300 $\mu g/m^3$ can be measured automatically (Wu et al., 2007a, 2007b).

For the measurement of organic carbon (OC) and elemental carbon (EC) concentrations, research has focused on the thermal-optical method, which has been accepted as the most reliable method for carbon analysis. Using high-temperature controls, micro-airflow accuracy controls, and high-precision carbon dioxide detection techniques based on the nondispersed infrared method, a highly cost-effective, practical and reliable OC/EC online analyzer was successfully developed (Ding et al., 2009b; Shen et al., 2011) (**Table 2**). Concentrations of OC/EC in the ambient aerosol could be more accurately measured using this type of OC/EC analyzer, which has a minimum detection limit of 0.5 $\mu g/m^3$.

To study the optical properties of aerosols, cavity ring-down spectroscopy (CRDS) technology was developed to monitor aerosol extinction properties (Dai et al., 1997) (**Table 2**). By combining long path lengths, high time resolution and high precision in this system, a low-cost, high-performance CRDS method with a 0.2 mol/(L·m) limit of detection was established. This level of performance fulfills the requirements for investigating aerosol extinction properties in both laboratory and field studies.

The AIOFM won a National Science and Technology Award for the project titled “Environmental air quality and pollution optical monitoring system and its applications” in 2007. The awarded urban air quality monitoring system was certified for the automatic monitoring of the atmosphere in China and was installed in more than 400 automatic weather stations for urban air quality monitoring and forecasting. The monitoring system was also successfully applied during several events, including the 2008 Beijing Olympic Games and the 2010 Guangzhou Asian Games (Richard, 2008; Liu et al., 2009b).

2.2 Laboratory measurements

We recently developed ATOF-MS for the online analysis of the chemical composition, size and mixing state of fine particles. We used ATOF-MS along with 2-D GC, GC-MS, HPLC-MS-MS, IC and ICP-MS for the systematic analysis of the organic and inorganic compositions of $PM_{2.5}$. To explain $PM_{2.5}$ field observations and to define parameters for model simulation, the RCEES developed a platform with *in situ* Raman spectroscopy, FT-IR and online mass spectrometry to study the mechanisms and kinetics of homogeneous and heterogeneous atmospheric processes and the physical and chemical properties of aerosol.

For smog chamber simulation studies, the GIG, in collaboration with Prof. John Seinfeld of the California Institute of Technology (Caltech), has constructed a large indoor smog chamber with a 30 m^3 Teflon reactor. Compared with the current smog chamber at Caltech, the smog chamber at the GIG is superior in terms of temperature control, measurement equipment and the ability to incorporate online optical measurements (**Table 3**). The smog chamber can precisely control temperature from –10°C to 40°C and has equipment, including HR-TOF-AMS, ATOF-MS and PTR-TOF-MS, for the online analysis of the chemical composition, particle sizes and optical properties of aerosols and trace gases. The chamber can satisfy the needs of laboratory simulation studies of atmospheric gas-phase reactions and secondary aerosol formation.

The ICCAS has built a system combining a kinetic reactor and a smog chamber that can conduct kinetic and static simulations with the simultaneous detection of gas and particle species (**Table 3**). Using this combined system, we can analyze the free radical reaction process and comprehensively detect variations in chemical compositions, particle morphologies, particle sizes and the mixing states of aerosols in the secondary particle formation process. In addition, a hygroscopicity tandem differential mobility analyzer and accompanying CRDS technology have also been developed to accurately quantify the relationships between the physicochemical properties and general characteristics of haze formation.

2.3 Long-term field observations

Since December 2007, the IAP has maintained a monitoring network for atmospheric pollution that includes 25 stations (**Fig. 1**), covering an area of 25,000 km^2 over northern China (Xin et al., 2010; Ji et al., 2011; Tang et al., 2012). With data from long-term systematic observations,

Table 3 Smog chambers in CAS institutes

Institutes	Function	Volume (m^3)	Facilities	Temperature control	Pure air	Wall loss rate	Ozone dark decay
GIG	Simulation of SOA formation and evolution	30	HR-TOF-AMS, ATOF-MS, PTR-TOF-MS, SMPS, HTDMA, O_3-NO_x-SO_2-CO analyzer, PILS-ICGC-FID/MSD/ECD, HPLC	–10~40°C (± 0.5°C);	NHMCs < 500 ppt; NO_x < 40 ppt; No detectable particles	$0.17\ hr^{-1}$	$1.1 \times 10^{-4}\ min^{-1}$
ICCAS	Gas phase reaction process; Secondary aerosols formation and aging	2.5	PTRMS, HTDMA, DMA-APS, SMPS, CRDS, Nephelometer,VUV-TOFMS, HONO-NO_x-SO_2-O_3 analyzer, IR, Raman, GC, LC, CIMS	25–50°C	CH_4, CO, RCH, H_2, O_3, H_2S, SO_2, NO_x < 1 ppb; No detectable particles	$0.09\ hr^{-1}$	$1.9 \times 10^{-4}\ min^{-1}$

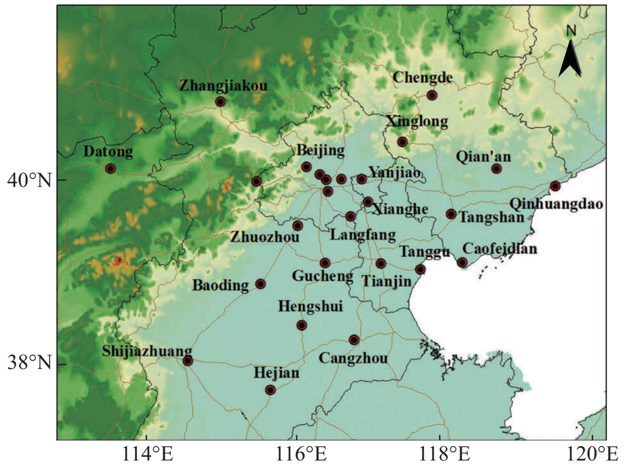

Fig. 1 Air Quality Network over Northern China.

scientists at the IAP obtained spatial-temporal patterns of $PM_{2.5}$ levels. These data have provided the scientific basis for regional air pollution control strategies. As an example, the IAP network worked jointly with Ministry of Environmental Protection monitoring stations to offer important scientific support in guaranteeing good air quality during the 2008 Olympic Games (Xin et al., 2010; Ji et al., 2011; Tang et al., 2012).

At one regional station (i.e., Wanqingsha in the PRD region), the GIG has been conducting intensive field observations of concentration, chemical composition and optical properties of $PM_{2.5}$ since 2007. In addition, the GIG has conducted observations of secondary aerosol precursors and other trace gases (Zhang et al., 2010; Ding et al., 2011, 2012; Wang et al., 2012a). To achieve good air quality during the 2010 Asia Games, which were held in Guangzhou, the GIG worked with the Guangzhou Environmental Monitoring Center (GEMC) and the Foshan Environmental Monitoring Center to conduct a special investigation of air particulate matter pollution to reduce haze in the Guangzhou-Foshan region. During the 2010 Asian Games, the GIG reported twice per day to the local Environmental Protection Bureau regarding the atmospheric chemical components that impair visibility and precursors of ozone and secondary organic aerosols. In addition to a joint superstation for air quality that was co-established in urban Guangzhou by the GIG and the GEMC, the GIG has recently established background stations in east-central China.

The IUE has an atmospheric superstation on its campus and cooperates with government environmental protection institutions in the Fujian Province to study complex air pollution at 14 stations in the city clusters on the west coast of the Taiwan Strait (Wenzhou, Ningde, Fuzhou, Fuqing, Pingtan, Putian, Quanzhou, Zhangzhou, Xiamen and Shantou). In addition to the air pollutants that are monitored by local environmental monitoring centers, the IUE uses these 14 stations to observe $PM_{2.5}$, O_3, VOCs and the chemical compositions of aerosols (Chen et al., 2011; Zhao et al., 2011a, 2011b).

The IEE has collected filter-based $PM_{2.5}$ samples since March 2002 at a station within its campus. The IEE has obtained daily $PM_{2.5}$ concentrations and measurements of elemental, ionic and carbonaceous $PM_{2.5}$ components. This monitoring effort has provided the longest data series of continuous, daily, and mean concentrations and chemical components of $PM_{2.5}$ in China. Early in 2003, the IEE organized a simultaneous monitoring of $PM_{2.5}$ in China's 14 key cities and compiled information about concentrations, elemental compositions, water-soluble inorganic ions, organic and elemental carbon, organic compositions, stable isotopes and water-soluble metals constituting $PM_{2.5}$ in these cities (Wang et al., 2006c; Cao et al., 2007, 2011; Han et al., 2009).

3 Control strategies and technologies

3.1 Control the emission of $PM_{2.5}$ and its gaseous precursors

3.1.1 Sources of $PM_{2.5}$

Advanced studies of source apportionment proved that the source of PM_{10} was mainly industrial activity, dust and biomass burning. However, the sources of $PM_{2.5}$ varied significantly: automobiles and the related industries contributed up to 50%, steel manufacturing and the chemical and electronic industries produced 35%, thermal power plant emissions accounted for 8%, and residential warming, catering and farming and animal husbandry produced nearly 7% (Zhang et al., 2009). The reasons why automobiles and the related industries are the top contributors include gasoline quality, engine exhaust, tail gas treatment, gas station emissions, garages and dust caused by automobile traffic.

3.1.2 How to control $PM_{2.5}$-induced haze

To mitigate serious haze pollution, the reduction of $PM_{2.5}$ primary emissions and gaseous precursors (e.g., SO_2, NOx, NH_3 and VOCs) is critical (Pan et al., 2010; Sun et al., 2009, 2011b; Tang et al., 2009, 2012). Because the chemical composition of $PM_{2.5}$ varies spatiotemporally, the factors controlling haze differ across seasons and regions (Sun et al., 2011a; Ji et al., 2011; Xin et al., 2010). Therefore, the priorities of programs for reducing haze should be changed seasonally and spatially. The composition of $PM_{2.5}$ in Beijing, for example, was equally produced by original emissions, photochemical production and regional transport (Streets et al., 2007; Xin et al., 2010). Because much of the air pollution experienced in Beijing is attributed not only to local sources but also to sources all over northern China (Wang et al., 2012b; Sun et al., 2011b; Ji et al., 2011), control measures that are only implemented in Beijing cannot reduce pollutants to acceptable levels. To mitigate $PM_{2.5}$ pollution in the future, China should promote the joint prevention and control of air pollution, which will be a major challenge.

The physical and chemical compositions of $PM_{2.5}$ in different climates and meteorological zones across China differ from Beijing (Wang et al., 2010b; Sun et al., 2010; Zhang et al., 2009b), which underscores the need for systematic and comprehensive comparison studies in several regions of China to clarify how $PM_{2.5}$ results in haze.

3.1.3 Possible control strategies and suggestions

Industrial restructuring: China needs to expand economic system reforms, change the way in which the economy is grown, and consider external demand for sustainable economic development.

Industrial layout: Considering the topography over northern China and that regional pollution becomes more evident when southwesterly and southeasterly winds prevail in the BTH region, the industrial layout in the BTH region should be reconsidered as a whole. Industries with high energy consumption should be relocated to the eastern coastal and northwestern mountainous areas to favor the dispersion and deposition of air pollutants away from urban areas.

Environmental protection measures: The use of dust, sulfur, and NOx removal technology by coal-burning power plants should be expanded. In addition, the efficient operation and regulatory independence should be strengthened for air pollutant removal equipment.

Use of clean energy: Improving petroleum product quality and promoting the use of clean energy, including low-sulfur coal, natural gas, and solar and wind power, are guaranteed ways to decrease air pollutants originating from fossil fuels.

Evaluation of new emission sources: Uncertainties regarding emission sources, including the effects of oil sulfur content, cooking oil fumes, and various NH_3 emission sources, should be meticulously evaluated. For example, the possible NH_3 sources in the BTH region include nearshore operations, stock farming, catalytic converters in automobiles, NOx removal instruments, fertilizers, and waste disposal. After each source is thoroughly investigated, detailed control measures for each source can reduce $PM_{2.5}$ by as much as 15%.

3.2 Technique development for the removal of $PM_{2.5}$ and its precursors

3.2.1 Technique development for the removal of $PM_{2.5}$

Because multiple pollutants exist in flue gas, the IPE has also studied inorganic membrane integrated multipollutant controls and active carbon coordinated multipollutant controls. To address the presence of fine particles in industrial flue gas, collaboration between the IPE and Jiangsu Yuda Co. Ltd. has resulted in a high-efficiency hybrid particulate capture technology. For example, a high-efficiency hybrid particulate collector was developed with filter cleaning technology for fine particulates. After the electrode configuration and gas distribution were optimized, the efficiency reached 99.95% (**Table 4**). This technology has been applied in industrial fine particle collection, and the outlet particulate levels met the latest national standards for dust. To date, the implementations of this technology have provided significant social and economic benefits, with an output of approximately 300 million CNY and a 100,000-ton reduction in particulates per year.

3.2.2 Technique development for the removal of NOx

The RCEES successfully developed advanced catalyst systems for the selective catalytic reduction of NOx by ammonia (NH_3-SCR) or by hydrocarbons (HC-SCR): these species are extremely effective in the reduction of NOx in heavy-duty diesel engines (He and Yu, 2005; Liu et al., 2008b; Shan et al., 2011a, 2011b). Recently, a production line for catalytic converters was built by the China National Heavy Duty Truck Group Corp.; this line will be activated to meet the requirements of the China IV standards (implemented in 2012) for heavy-duty diesel vehicles (He et al., ZL02100669.5, ZL02157917.2, ZL 200710121422.4) (**Table 4**).

The RCEES successfully developed a series of high-/medium-/low-temperature NH_3-SCR catalyst systems that effectively removed NOx from the flue gas of coal-fired

Table 4 Control technologies

Species	Instruments	Principle of equipments	Efficiency (%)	Patent number
$PM_{2.5}$	Deflector	Automatically adjust gas flow volume into the bag filter		ZL200510095430.7
	Hybrid particulate capture	An electrostatic precipitator combined with a bag filter	99.95–99.9	PCT/CN2007/001555
NO_x	SCR catalyst	Reduce NO_x selectively to N_2 in exhaust with lean O_2	82.6–100	ZL02100669.5
	SCR catalyst	Reduce NO_x selectively to N_2 in exhaust rich in O_2	82–85.5	ZL02157917.2
	SCR catalyst	Reduce NO_x selectively to N_2 by NH_3	25–100	ZL200710121422.4
SO_2	Composite internal	Induce the collision and mass transfer of particles		US789116B2
	Inner-outer circulating fluidize bed for desulfurization	Semi-dry desulfurization by $Ca(OH)_2$ absorption	90–95	ZL200610072800.X

power plants and industrial boilers in the presence of coexisting pollutants (Liu et al., 2009a, 2010a; Liu and He, 2010; Shan et al., 2011a, 2011b). The IUE also successfully developed a regeneration method for commercial deNO_x catalysts and obtained good regeneration efficiencies (Shang et al., 2011, 2012) (**Table 4**).

3.2.3 Technique development for the removal of SO_2

To control the SO_2 flue gas from coal-fired boilers and sintering machines, the IPE has developed two desulfurization technologies: semi-dry desulfurization in an inner-outer circulation fluidized bed (IOCFB) and wet desulfurization by carbide (**Table 4**). The IOCFB desulfurization improves the reliability and stability of traditional circulating fluidized beds, the efficiency of which greatly depends on the unit load, the coal type and the desulfurization agent. Several patents have been authorized, and the first industrial demonstration of Chinese sintering gas desulfurization using the IOCFB technology was performed in 2006. Wet desulfurization by carbide overcomes the problems caused by the high-pH carbide slurry supernatants and makes the supernatant concentration adjustable with the SO_2 levels. These advantages improve the industrial applications of carbide utilization and desulfurization. To date, the two technologies have been applied in more than 30 desulfurization demonstrations with an output of more than 300 million CNY and a reduction in accumulated SO_2 levels of greater than 180,000 tons per year.

4 Challenges of China due to the new $PM_{2.5}$ standard

The World Health Organization (WHO) issued an annual average concentration of 10 $\mu g/m^3$ as the long-term guideline value for $PM_{2.5}$ and a daily average concentration of 25 $\mu g/m^3$ as the short-term guideline value for $PM_{2.5}$. In addition to the guideline values, interim targets (IT) were defined for $PM_{2.5}$ for long-term exposure: annual mean $PM_{2.5}$ concentrations of 35, 25, and 15 $\mu g/m^3$ were selected as the IT-1, IT-2, and IT-3 levels, respectively. In addition to the long-term guideline values, three IT were defined for $PM_{2.5}$ for short-term exposure: daily mean $PM_{2.5}$ concentrations of 75, 50, and 37.5 $\mu g/m^3$ were selected as the IT-1, IT-2, and IT-3 levels, respectively. The new $PM_{2.5}$ standards directly mirror the WHO IT-1 guideline values issued by the MEP, with an annual mean $PM_{2.5}$ concentration of 35 $\mu g/m^3$ and a daily mean $PM_{2.5}$ concentration of 75 $\mu g/m^3$ (**Table 1**). However, it will be difficult for China to meet these standards by 2016. Therefore, a detailed analysis of how to meet these standards should be conducted.

According to data released by the Beijing Municipal Environmental Protection Bureau, the annual PM_{10} concentration in Beijing is approximately 120 $\mu g/m^3$. According to that the ratio of $PM_{2.5}$ to PM_{10} is 60%, the annual average $PM_{2.5}$ concentration is 72 $\mu g/m^3$, which is approximately twice the new annual standard. According to the results obtained by the air quality network consisting of more than 10 stations that monitored $PM_{2.5}$, the frequency at which $PM_{2.5}$ exceeds 75 $\mu g/m^3$ is 50%. However, the frequency at which the current standard is exceeded is only 20%. To reduce PM levels, more research that acknowledges the current state of the economy, climate and environment must be conducted. Then, new $PM_{2.5}$ guideline values can be established that satisfy both human health concerns and sustainable economic development.

In 1987, the United States proposed PM_{10} air quality standards. After the PM_{10} problems were solved, $PM_{2.5}$ standards were issued in 1997. The implementation of $PM_{2.5}$ standards will be beneficial for the general public in China, and the new standards will help the Chinese Government to improve air quality and respond to public demand. Importantly, public participation and government attention and supervision will be improved, which are likely to accelerate the early implementation of the $PM_{2.5}$ standards in China. However, once the Ministry for Environmental Protection formally introduces new $PM_{2.5}$ standards, local governments will face significant challenges.

Acknowledgments

This work was supported by the National Nature Science Foundation of China (No. D010504) and the Strategic Priority Research Program of the Chinese Academy of Sciences (No. XDB05000000).

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