Emission standards and control of $PM_{2.5}$ from coal-fired power plant

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Preface

This report has been produced by IEA Clean Coal Centre and is based on a survey and analysis of published literature, and on information gathered in discussions with interested organisations and individuals. Their assistance is gratefully acknowledged. It should be understood that the views expressed in this report are our own, and are not necessarily shared by those who supplied the information, nor by our member countries.

IEA Clean Coal Centre is an organisation set up under the auspices of the International Energy Agency (IEA) which was itself founded in 1974 by member countries of the Organisation for Economic Co-operation and Development (OECD). The purpose of the IEA is to explore means by which countries interested in minimising their dependence on imported oil can co-operate. In the field of Research, Development and Demonstration over fifty individual projects have been established in partnership between member countries of the IEA.

IEA Clean Coal Centre began in 1975 and has contracting parties and sponsors from: Australia, Austria, China, the European Commission, Germany, India, Italy, Japan, Poland, Russia, South Africa, Thailand, the UK and the USA. The Service provides information and assessments on all aspects of coal from supply and transport, through markets and end-use technologies, to environmental issues and waste utilisation.

Abstract

Fine particulate matter, $PM_{2.5}$, can include SO_2, NOx, toxic volatile organic compounds, heavy metals, water and biogenic organic species. $PM_{2.5}$ can be emitted directly or form in the atmosphere from the reactions of other pollutants. Coal-fired power plants are a major source of $PM_{2.5}$. There are international and national emission standards to limit $PM_{2.5}$. The standards for Australia, China, Germany, India, Indonesia, Japan, South Africa, Thailand and the USA are described. There are various ways to measure $PM_{2.5}$ in the atmosphere. The emission of $PM_{2.5}$ from coal-fired plants can be controlled pre-combustion, in-combustion and post-combustion. Pre-combustion control is by coal selection and coal preparation. In-combustion control is by optimising combustion and the injection of sorbents into the flame zone. There are various methods of post-combustion control of $PM_{2.5}$ emissions, including conventional particle emission control devices (PECD) such as electrostatic precipitators (ESP) and fabric filters, and innovative PECDs such as flue gas conditioning and wet ESPs. Other methods of post-combustion control include agglomeration, various hybrid systems, and multi-pollutant control systems. Recent developments in PM emission control technologies are reviewed.

Acronyms and abbreviations

AAQ	ambient air quality
AAQS	ambient air quality standards
AHPC	Advanced Hybrid Collector
BACT	best available control technology
BAT	best available technology
BAT-AELs	BAT associated emission levels
BHEL	Bharat Heavy Electricals Limited (India)
BREF	BAT reference document
CAA	Clean Air Act (USA)
CAIR	Clean Air Interstate Rule (USA)
CEN	Comité European de Normalization
COHPAC	Collector Compact Hybrid Particulate Collector
CPCB	Central Pollution Control Board (India)
CPM	condensable particulate matter
CSAPR	Cross-State Air Pollution Rule (USA)
DEA	Department of Environmental Affairs (South Africa)
EC	European Commission
ELV	emission limit value
EFF	ESP-FF hybrid system
EPA	Environmental Protection Agency (USA)
EPA	Environment Protection Authority (Australia)
EPRI	Electric Power Research Institute (USA)
ESFF	electrostatically stimulated fabric filter
ESP	electrostatic precipitators
EU	European Union
FF	fabric filter
FGC	flue gas conditioning
IED	Industrial Emissions Directive (EU)
IPPC	integrated pollution prevention and control
ISO	International Organization for Standardization
LCPD	Large Combustion Plant Directive (EU)
LAER	lowest achievable emissions rate
MEP	Ministry of Environmental Protection (China)
MOE	Ministry of the Environment (Japan)
MSC	multistage collector
NAAQS	National Ambient Air Quality Standards (USA)
NDRC	National Development Reform Commission (China)
NEA	National Energy Administration (China)
NEPC	National Environment Protection Council (Australia)
NEPM	National Environment Protection Measure (Australia)
NHMRC	National Health and Medical Research Council (Australia)
NPC	National People's Congress (China)
NSPS	New Source Performance Standards (USA)
NSW	New South Wales (Australia)
PCD	Pollution Control Department (Thailand)
PJFF	pulse jet fabric filter
PM	particulate matter

PM_{10}	particulate matter below 10 µm in diameter
$PM_{2.5}$	particulate matter below 2.5 µm in diameter
POEO	Protection of the Environment Operations (Australia)
PSD	Prevention of Significant Deterioration (USA)
SIP	State Implementation Plan (USA)
SPL	sound pressure level
TEOM	tapered element oscillating microbalance
TNP	Transitional National Plan (USA)
TSP	total suspended particulate
VOC	volatile organic compound
WESP	wet electrostatic precipitator
WHO	World Health Organisation

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1 Introduction

Considerable efforts have been made over the years to regulate, control and prevent the emission of pollutants from coal-fired power plants. The coal industry is facing stringent emission regulations, to limit the release of sulphur dioxide (SO_2), oxides of nitrogen (NOx), toxic volatile organic compounds (VOCs), heavy metals such as mercury, and particulate matter (PM). PM can contain any or all of the aforementioned chemical species or their compounds, plus water and biogenic organic species. The chemical composition of PM varies with coal type, power plant design and location, and also with ambient conditions such as temperature and wind direction.

PM is usually classified by particle size because of the wide variation and complexity of its chemical composition. In this report, the following definitions are used:

- PM_1 particles less than 1 µm in diameter, known as ultra-fine or submicron particles;
- $PM_{2.5}$ particles less than 2.5 µm in diameter, fine particles;
- PM_{10} particles less than 10 µm in diameter, coarse particles.

The surface area of the smallest particles is greater than that of larger ones. For example, one gramme of 0.1 µm particles has a surface area of 60 square metres, 10 times the surface area of a gramme of 1 µm particles. The large surface area means that fine $PM_{2.5}$ can be enriched in toxic substances. Due to their small size, $PM_{2.5}$ particles can remain suspended in the air for several days to a week or more, and tend to be more homogeneously distributed with distance from the emission source. $PM_{2.5}$ can be inhaled into human respiratory systems and travel deep into the lungs causing health problems, such as lung cancer and other cardiopulmonary diseases. A significant fraction of the $PM_{2.5}$ particles have a diameter near the wave length of light, so that they scatter light efficiently and reduce visibility (Pui and others, 2014). This makes $PM_{2.5}$ a major cause of smog in cities and elsewhere.

$PM_{2.5}$ are usually classified as primary and secondary particles. Primary $PM_{2.5}$ particles are those that are emitted directly to the air from stationary or moving sources. Secondary $PM_{2.5}$ are formed from reactions with gaseous pollutants, such as SOx, NOx, NH_3, and VOCs, through nucleation, condensation, coagulation and evaporation of water droplets in which the gases are dissolved and reacted. Primary $PM_{2.5}$ and the precursors of secondary fine particulates, SO_2 and NOx, are emitted into the atmosphere from various sources, including coal-fired power plants. Figure 1 shows the share of $PM_{2.5}$, NOx and SO_2 emissions by sector group in the European Union (EU) emitted in 2013. Only 6% of $PM_{2.5}$ was from energy production and distribution, but 56% of SO_2 and 21% of NOx came from this source (European Environment Agency, 2015). However, the composition of $PM_{2.5}$ is mostly dominated by sulphates and nitrates formed from SOx or NOx precursors. Therefore, coal-fired power plants contribute significantly to $PM_{2.5}$ concentrations in the air through the emission of SOx and NOx. According to the Chinese National Bureau of Statistics, in 2005, PM emissions from coal-fired power plants accounted for 44.6% of total PM emissions in China (Yao and others, 2009). Control of PM emissions and their precursors from coal-fired power plant are necessary to mitigate their environmental and health impacts, especially in countries where coal is the main energy source for power generation, such as China, India and South Africa.

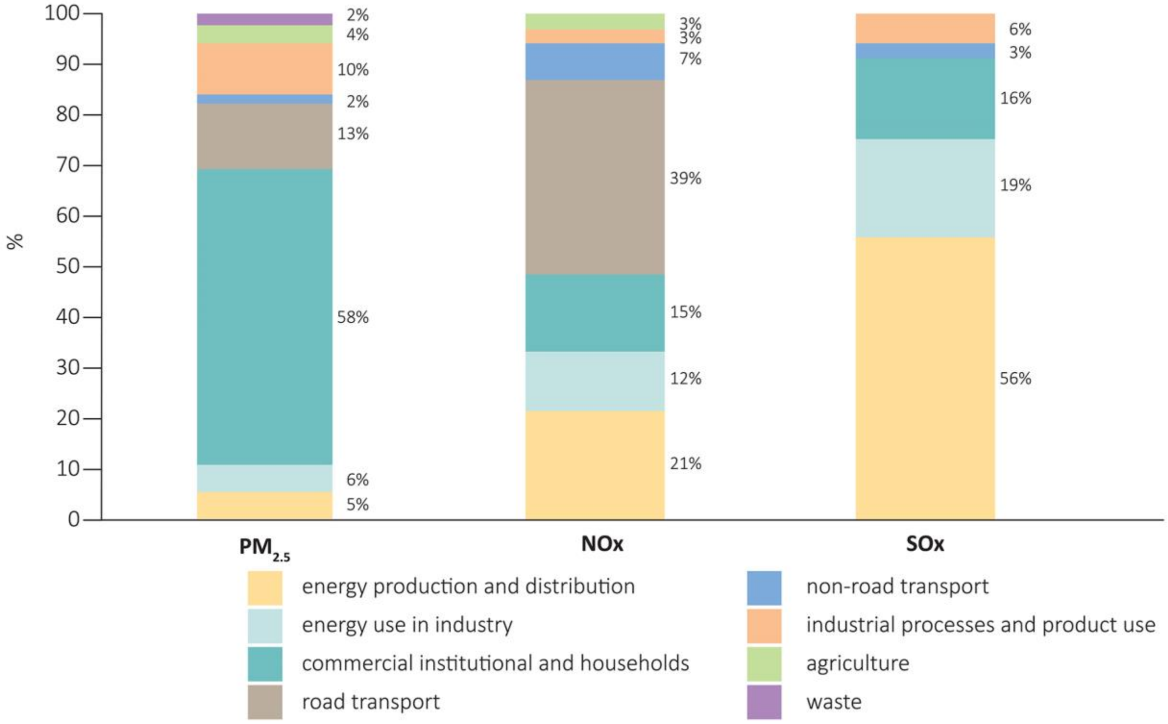

Figure 1 **$PM_{2.5}$, NOx, and SO_2 emissions by the sector group in Europe in 2013** (European Environment Agency, 2015)

During the last decade, a large amount of research and development has been carried out on PM, especially on $PM_{2.5}$. Emission regulations and testing and measuring standards for $PM_{2.5}$ have been developed and implemented. Following the 2005 World Health Organisation (WHO) guidelines on $PM_{2.5}$, some countries and the EU have implemented emission standards for stationary sources. The International Organization for Standardization (ISO) has issued three $PM_{2.5}$ measurement standards, and the US Environmental Protection Agency (EPA) has also updated its measuring methods to specifically include $PM_{2.5}$. These developments are reviewed in this report.

The report begins by describing international and selected countries' national air quality and PM emission standards for stationary sources that are relevant to coal-fired power plants. Emission standards for SO_2 and NOx are included since they are precursors of secondary fine PM. International and national measurement standards are summarised in Chapter 3. Finally, recent developments in PM emission control technologies are reviewed.

2 $PM_{2.5}$ emission standards

Clean air is considered to be a basic requirement for human health and well-being. The World Health Organisation (WHO) has produced air quality guidelines for reducing the health impacts of air pollution worldwide. The WHO guidelines updated in 2005 include thresholds and limits for PM, NO_2 and SO_2, shown in Table 1 (WHO, 2006). Based on known health effects, both 24-hour (short-term) and annual mean (long-term) guidelines are needed as indicators of PM pollution. For SO_2, the recommended guideline values are not linked to those for PM. The 24-hour guideline might be difficult for some countries to achieve, so a stepped approach using an interim goal of 50 µg/m³ for controlling vehicle emissions, industrial emissions and/or emissions from power production is recommended.

Table 1 Air quality guidelines for NO_2, SO_2 and PM (WHO, 2006)

Pollutants	Time period	ELVs, µg/m³
NO_2	1 hour	200
	annual	40
SO_2	10 minutes	500
	24 hours	20
$PM_{2.5}$	24 hours	25
	annual	10
PM_{10}	24 hours	50
	annual	20

Air quality standards are regulatory measures designed to achieve a desired level of air quality by regulating the amount of pollutants that can be emitted from a facility. Emission standards have had a major influence on cutting emissions from coal-fired power plants and other sources. Most commonly, parties establish emission standards and emission limit values (ELVs) based on the best available technologies (BAT), and require emission data to be reported as specified in the standards.

When Sloss (2004) reviewed the importance of $PM_{10/2.5}$ for IEA CCC in 2004, there were no international emission standards or guidelines which applied directly to emissions of $PM_{2.5}$ from coal-fired utilities. The WHO did not have guidelines for $PM_{2.5}$ emission control. In Europe, a working group under the Clean Air Europe programme had issued a draft recommendation that $PM_{2.5}$ should be made the principle metric for assessing exposure to particles, and suggested in 2010 an annual average limit of 12–20 µg/m³ and a 24-hour average limit of ~35 µg/m³ that should not be exceeded on more than 10 days per year. Few countries had set up a national limit for fine particulates. The US EPA issued national ambient air quality standards in 1997 with annual limits of 15 µg/m³ and daily limits of 65 µg/m³ for $PM_{2.5}$. But the Supreme Court ruled that the US EPA could not start implementing the standards until the US EPA and the states had collected at least three years of monitoring data to determine areas of non-compliance.

During the last decade, particulate matter emission regulations, especially for PM_{10} and $PM_{2.5}$, have developed rapidly. Today, $PM_{2.5}$ from coal-fired power plants are regulated as PM in many countries. Ten countries and regions have been selected for further discussion. They are either IEA CCC member countries or amongst the 15 top coal consuming countries in the world (IEA, 2014). The emission standard information is mainly taken from the IEA CCC emission standards database, unless otherwise stated. Since a large portion of total $PM_{2.5}$ is made up of secondary particles, such as sulphate and nitrate particles formed through chemical reactions, legislation on SO_2 and NOx emissions are relevant to $PM_{2.5}$ control, and therefore are included. Standards for power plants smaller than 50 MW are not covered in this report.

2.1 Australia

Australia does not have national air quality emissions standards. Instead Environment Protection Authorities in the States and Territories set such standards. The Australian National Environment Protection Measures (NEPMs) were set up by the National Environment Protection Council (NEPC). Implementation of these measures falls to State and Territory Environment Protection Authorities (EPAs). These can adopt broader or more stringent standards than those provided for by the NEPMs, but may not adopt lower standards. The two NEPMs relevant to air pollutants are the *National Environment Protection (Ambient Air Quality) Measure* (Australian NEPC, 2003) and the *National Environment Protection (National Pollutant Inventory) Measure 1998* (Australian NEPC, 2008).

The *National Environment Protection (Ambient Air Quality) Measure* (Air NEPM) was established in June 1998. It provides a nationally consistent framework for monitoring and reporting six criteria air pollutants, namely carbon monoxide, nitrogen dioxide, ozone, sulphur dioxide, lead and particulate matter (PM_{10}). In 2003 it was amended to include fine particulate matter, $PM_{2.5}$. The *Air NEPM* sets national air quality standards for each of these pollutants, which are legally binding, except the standards for $PM_{2.5}$ which are only advisory. A review was released by the Australian NEPC (2011) in September 2011 which lists 23 recommendations, including the introduction of compliance standards for $PM_{2.5}$. In April 2014, Ministers signalled their intention to vary the *Air NEPM* for particles to reflect the latest scientific understanding of the health risks. Consequently, a more stringent reporting standard for particle pollution ($PM_{2.5}$ and PM_{10}) may be established. The Environment Ministers are working towards establishing a National Clean Air Agreement. This will focus on actions to reduce air pollution and improve air quality through cooperative action between industry and government at the national, state and local level. The Agreement will incorporate a range of existing, new and complementary measures to improve air quality. The discussion paper, *Working towards a National Clean Air Agreement*, was released in February 2015. On 15 July 2015, the State Environment Ministers committed to finalise the Agreement and its initial work plan before the end of 2015 (Australian Department of Environment, 2015).

The *Air NEPM* set a current goal for ambient air quality. The guidelines for $PM_{2.5}$ are 25 $\mu g/m^3$ for annual and 8 $\mu g/m^3$ for 24 hours which are in line with the WHO. The guidelines for NOx and SO_2 concentrations in air are measured in ppm and are weaker than those for the WHO and the EU. The annual average for NOx is 62 $\mu g/m^3$ comparing to 40 $\mu g/m^3$ for both the WHO and the EU.

The current *National Environment Protection (National Pollutant Inventory) Measure*, published in 2008, lists 93 reportable substances. Industrial facilities that use or produce any of these substances (according to specified thresholds) are required to estimate and report emissions every year. These include emissions of nitrogen oxides, sulphur dioxide, PM_{10} and $PM_{2.5}$ from power plants.

The *National Guidelines for Control of Emission of Air Pollutants from New Stationary Sources* was first published by the National Health and Medical Research Council (NHMRC) in 1985 and was rescinded on 29 February 2000 (NHMRC, 2000). The guidelines set emission limits from industrial processes but only covered new plants and installations. The limits for coal-fired power plants are listed in Table 2 as reference. However, unlike other countries, the limit for SOx only covers sulphuric acid mist and sulphur trioxides, measured as SO_3.

Table 2 Australian emission limits guidelines for NOx, SOx and PM from coal-fired power plants (Australia NHMRC, 2000)

Pollutant	**Plant type**	**Emission limits, mg/m^3**
NOx (as NO_2)	Power generating boiler >30 MWe	800
SOx (as SO_3)	Fuel burning equipment	200
PM	All power plant boilers	80

As mentioned above, each Australian state and territory has its own Environmental Protection Act under which regulations and emission standards are set up by the independent statutory body, namely the EPA. Victoria introduced its Environment Protection Act in 1970, while the Northern Territory's Act only came into force in November 2014. The rest of the states and territories issued their Environment Protection Acts between 1986 to 1997. There are no specific regulations for emissions from stationary sources in the Australian Capital Territory and Queensland. The Northern Territory follows the national AQS of the Ambient Air Quality NEPM, and has set up a monitoring plan for the six criteria air pollutants (Australian Northern Territory EPA, 2001). Western Australia only has a limit of 0.25 ppm per year for SO_2 emissions in the Goldfields residential area (Australian WA EPA, 2003).

Under the Environment Protection Act 1993, the EPA in South Australia set out the *Environment Protection (Air Quality) Policy 1994* and amended it in 2005 (Australian SA EPA, 2005). The emission limits relevant to coal combustion equipment are listed in Table 3.

Table 3 South Australian emission limits for NOx, SOx and PM from coal-fired power plants (Australian SA EPA, 2005)

Pollutant	Plant size	Emission limits, mg/m^3
NOx (as NO_2)	≥250 MWe	700[1]
Sulphuric acid mist and SO_3 (as SO_3)	any	100
PM	≥100 MJ/h	250[2]

[1] Reference conditions are 0°C, 101.3 kPa on a dry flue gas basis with 7% O_2 in the flue gas (calculated as NO_2)

[2] Reference conditions are 0°C, 101.3 kPa on a dry flue gas basis with 12% CO_2 in the flue gas

The jurisdiction of the EPA in Tasmania includes environmental management and pollution control matters deriving from the *Environmental Management and Pollution Control Act 1994.* The emission limit (specified as in-stack concentrations) for pollutants discharged to the atmosphere are set out in the *Environment Protection Policy (Air Quality) 2004* (Australian TAS EPA, 2004). It was reviewed in May 2015 but no changes were made. The emission limits given in the policy relevant to coal combustion equipment are shown in Table 4 but only apply to new installations and facility upgrades.

Table 4 Tasmania emission limits for NOx, SOx and PM from new and upgraded coal-fired power plants (Australian TAS EPA, 2004)

Pollutant	Plant size	Emission limits, mg/m^3
NOx (as NO_2)	<30 MWe	500
	≥30 MWe	800
Sulphuric acid mist and SO_3 (as SO_3)	any	100
PM	any	100

Reference conditions are 0°C, 101.3 kPa on a dry flue gas basis with 7% O_2 in the flue gas (calculated as NO_2).

The limits do not apply to boilers with a heating capacity (as determined by the apparatus by which it is heated) of less than 110 MJ/h.

In Victoria, the *State Environment Protection Policy (Ambient Air Quality)* sets air quality objectives and goals for Victoria (Victoria Government, 1999). Victoria adopted the requirements of the *National Environment Protection (Ambient Air Quality) Measure*, discussed earlier.

The *State Environment Protection Policy (Air Quality Management)* established the framework for managing emissions into the air in Victoria from all sources (Australian Victoria Government, 2001). It addresses ambient (or regional) air quality, the management of particular sources such as industry, and local air quality impacts. Emission limits applicable for coal combustion equipment are given in Table 5. More stringent emission limits have been set for new stationary sources in the Air Quality Control Regions, namely Port Philip Air Quality Control Region and Latrobe Valley Air Quality Control Region. There is a separate NOx emission limit for new coal-fired power plants. A new stationary source is one in which development works are yet to commence. (Reference conditions for the emission limit values are 0°C, 101.3

kPa and on a dry flue gas basis for particulate matter, but with the additional requirement of 12% CO_2 in the flue for combustion particles, and 7% O_2 in the flue gas for NOx.)

Table 5 Victoria emission limits for NOx, SOx and PM from stationary sources (Australian Victoria Government, 2001)

Pollutant	**Emission limits, mg/m^3**	
	Existing sources	**New sources**
NOx (as NO_2)	1000[1]	500
		700[2] (coal-fired power plants ≥250 MWe)
SOx (as SO_3)	200	200
Combustion particles	500	250
Total PM	500	250

[1] Plant size is greater than 150,000 MJ/h, gross (heat input rate)

[2] This limit may be relaxed to 780 $\mu g/m^3$ in individual cases where it can be shown that 700 mg/m^3 is too restrictive in relation to such matters as the type of fuel being burned, existing emission control technology, and factors of health and safety.

The *Protection of the Environment Operations Act 1997* (POEO Act) provides the legal basis for environmental protection regulation in New South Wales (NSW), whilst the *Protection of the Environment Operations (Clean Air) Regulation 2010* (POEO Regulation) sets emission standards for air pollutants from power plants and industrial processes (Australian NSW EPA, 2010), (*see* Table 6). Under the POEO Act all power plants and industrial facilities require a licence to operate. The licence is additional to, and independent of, the POEO Regulation requirements and licence conditions may specify emission limits that are more stringent and/or include emission limits for pollutants not covered by the POEO Regulation. Tighter requirements may be due to the proximity of a plant to the to the local population. The NSW EPA is responsible for issuing the licences and for administering the POEO Regulation.

Table 6 NSW emission limits for NOx, SOx and PM from coal-fired plants (Australian NSW EPA, 2010)

Pollutant	Plant type		ELV, mg/m^3
NOx (as NO$_2$)	Any activity or plant (except boilers, gas turbines and stationary reciprocating internal combustion engines listed below)	Group 1, 2, 3, or 4	2500
		Group 5	2000
		Group 6	350
	Boiler used in connection with an electricity generating system with a capacity of less <30 MW	Group 1, 2, 3, or 4	2500
		Group 5 or 6	500
	Turbine used in connection with an electricity generating system with a capacity of ≥10 MW but < 30 MW	Group 1, 2, 3, or 4	2,500
		Group 5	150
		Group 6	90
SOx (as SO$_3$)	Group 1		200
	Group 2, 3, 4, 5 or 6		100
Total PM	Group 1		400
	Group 2, 3, 4		250
	Group 5		100
	Group 6		50

The emission values are measured hourly. Reference conditions for the emission limit values relating to:

- Group 1, 2, 3 or 4 facilities are 0°C, 101.3 kPa and on a dry flue gas basis with 12% CO$_2$ in the flue gas for particulate and 0°C, 101.3 kPa and on a dry flue gas basis for NOx
- Group 5 or 6 facilities are 0°C, 101.3 kPa and on a dry flue gas basis with 7% O$_2$ in the flue gas.

The plants in the different groups are classified by the date they started operation and the date of their pollution control approval was granted. Group 5 power plants started operation on or after 1 August 1997, and group 6 power plants started on or after 1 September 2005. Details can be found in NSW EPA POEO Regulation (2010) and on the IEA CCC emission standards database.

2.2 China

In China the Ministry of Environmental Protection (MEP is responsible for setting air quality standards. The Committee of the National People's Congress (NPC) issues the law.

In 1987, the NPC council enacted the *Law on the Prevention and Control of Atmospheric Pollutants,* which was revised in 1995 and 2000. China implemented the *Environmental Protection Law* in 1989 and made a first amendment in 2014, after 25 years. It established the framework for protecting the environment, including setting standards, assessing and limiting environmental impacts, fines for pollution, and bans on polluting technologies and facilities.

The *Air Pollution Protection Law* was implemented in 2000. In August 2015, draft amendments of this law were passed by the NPC with the purpose of strengthening pollution treatment from the source. The new law requires local governments to adjust the energy structure, promote clean and efficient use of coal, and ban low-quality coal for residential and domestic use. It also requires all coal-fired power plants to install emission control devices rather than only control emissions when the limits are exceeded. Mercury emission control was introduced for the first time (China NPC, 2015).

The *Ambient Air Quality Standards* (AAQS) (GB 3095-2012) were first published in 1996 and updated in 2012 by the Ministry of Environmental Protection. The standards have been implemented from 1 January 2016. Table 7 lists the emission limits for PM, SO_2 and NOx. The standards are divided into grade 1 and grade 2. Grade 1 covers protected areas, such as national parks, conservation areas, and designated historical sites. Grade 2 is for those in residential, commercial, cultural, industrial, and heavy traffic areas. Table 6 only includes the ELVs for grade 2 areas. China's air quality standards are less strict than the WHO and EU, especially for $PM_{2.5}$ which is three times that of the WHO value.

Table 7 China AAQS for PM, SO_2 and NOx for residential and industrial areas (China MEP, 2015)

Pollutants	Averaging time	ELVs, µg/m^3
NOx	annual	50
	24 hours	100
	1 hour	250
SO_2	annual[1]	60
	24 hours[2]	150
	1 hour[3]	500
PM_{10}	annual	70
	24 hours	150
$PM_{2.5}$	annual	35
	24 hours	75

[1] Annual average sampling must contain at least 324 days and each month must have at least 27 days (25 for February).

[2] Each day must have at least 20 hours sampling time.

[3] Each hour must have at least 45 minutes sampling time.

The ELVs for air pollutants from coal combustion are specified in *Emission standards of air pollutants for thermal power plants* (GB13223-2011). This standard was first set up by the MEP in 1991 and updated in 1996, 2003 and 2011 (China MEP, 2011). It applies to all pulverised coal combustion power generating boilers, and all coal-fired power generating boilers with unit capacity larger than 65 t/h, except for stokers. Gangue-fired power generating units with capacity larger than 65 t/h have to meet the emission standards for circulating fluidised bed (CFB) thermal power generating boilers. The gas turbines of integrated coal gasification combined cycle (IGCC) power generating units need to meet the emission limit values for natural gas-fired turbines. The ELVs for PM, SO_2 and NOx are given in Table 8. Key economic regions have stricter standards. The key regions include Beijing City, Tianjin City, Hebei Province, Yangzi River Delta, Pearl River Delta, Central Liaoning Province, Shandong Province, Wuhan City and surrounding areas, Changsha City, Zhuzhou City, Xiangtan City, Chengdu and Chongqing City, coastal areas of Fujian Province, Central and Northern Shanxi Province, Guanzhong Region of Shaanxi Province, Gansu Province, Ningxia Province, and Wulumuqi (Ürümqi, Xinjiang Uyghur Autonomous Region). The ELVs came into effect from 1 January 2012 for new plants and 1 July 2014 for existing plants. Existing plants are those which were in operation or had environmental permissions granted before 1 January 2012. New plants refer to new, upgraded or retrofitted plants whose environmental permissions were granted after 1 January 2012. All ELVs are calculated at reference conditions of 0°C, 101.3 kPa and dry flue gas basis with 6% O_2.

Table 8 ELVs for air pollutants from coal-fired power plants (China MEP, 2011)

Pollutant	Application	ELV, mg/m³	Location of monitoring
NOx (as NO_2)	all	100 (200[1])	Stack and flue
	key regions	100	
SO_2	new	100 (200[2])	
	existing	200 (400[2])	
	key regions	50	
PM	all	30	
	key regions	20	

[1] ELVs apply to arch fired furnaces, existing CFB power generating boilers, and power generating boilers commissioned or received approval for construction before 31 December 2003.

[2] ELVs apply to plants in Guangxi Zhuang Autonomous Region, Chongqing Municipality, Sichuan Province and Guizhou Province.

China MEP (2010) issued a *Guideline on Best Available Technologies of Pollution Prevention and Control for Coal-fired Power Plant Industry (on Trial)*. It listed the best available technologies to control PM, SOx and NOx, including their control efficiency.

The National Development Reform Commission (NDRC), MEP and National Energy Administration (NEA) jointly issued an action plan for coal-fired power plants for the same period on 12 September 2014 to reinforce the *Energy Development Strategy Action Plan (2014-2020)* which was published by the Chinese State Council (2014), The aim is to reduce China's high energy consumption through a set of measures and mandatory targets, and to promote more efficient, self-sufficient, green and innovative energy production and consumption. The plan specifies even stricter emission limits for future coal-fired power plants in 11 provinces in the developed eastern region: PM 10 mg/m³, SO_2 35 mg/m³, and NOx 50 mg/m³. All the existing coal power plants are required to upgrade and reconstruct their equipment and systems to meet these emission limits by 2020. For the central region, future plants shall meet these ELVs in principle. Western China is encouraged to meet these ELVs (NDRC and others, 2014). In order to speed up the air quality improving process, NDRC, MEP and NEA jointly issued another document on 11 December 2015 called the *Working Programme to Implement Ultralow Emission and Energy Saving Reconstruction for Coal*

Power Plants. In this working programme, the date to meet the ELVs has been brought forward to 2017 for the developed eastern region, 2018 for the central region, and 2020 for the less developed western region. By 2020, the whole country should meet these strict emission limits. All the power generation plants should be ultra-supercritical with capacity ≥ 600 MW (NDRC and others, 2015).

There are concerns that the new ELVs are set too high and go beyond the 2010 BAT guidelines. For example, PM ELV in GB13223-2011 was set as 30 mg/m^3 for all regions and 20 mg/m^3 for key regions. The new 2014 PM emission limits was even set as 10 mg/m^3. These PM ELVs are much higher than the guideline suggested BAT can achieve (*see* Table 9). The power generation sector has to upgrade the existing environmental control equipment in order to meet the new ELVs which may create huge economic impacts. Also, the low quality of coal used in some coal-fired power plants, makes is impossible to control PM emissions in China (Wang, 2014).

Table 9 Guideline on BAT and control levels for PM
(China MEP, 2010)

Boiler	SOx control technology	BAT	Control level, mg/m^3
PC	Wet FGD	ESP	<50
	Semi-dry FGD		<80
	Wet FGD	FF	<30
	Semi-dry FGD		<50
FBC	Semi-dry FGD	ESP	<100
		FF	<50

2.3 European Union

In Europe, emission standards take two main forms: regulations and directives. Once approved, regulations are directly applicable and binding on member states. Directives establish targets to be achieved, and it is up to the member states to decide the deadline, the form and method of implementation. The European Commission (EC)'s *Clean Air Policy Package* contains a collection of directives (*see* ec.europa.eu/environment/air/clean_air_policy.htm).

Stationary source emissions, including those from coal-fired power plants, were regulated by the *Integrated Pollution Prevention and Control (IPPC) Council Directive 2008/1/EC* of 15 January 2008 and *Large Combustion Plants Directive (LCPD) 2001/80/EC*. The former expired on 6 January 2014 and the latter ended its regulation period on 31 December 2015. On these dates the directives were overruled and replaced by the *Industrial Emissions Directive (IED) 2010/75/EU*. The *IED* merged seven pieces of legislation and entered into force on 6 January 2011. It was transposed into national legislation by member states from 7 January 2013. It sets out the main principles for the permitting and control of installations, including coal-fired power plants. Details of these principles can be found at http://ec.europa.eu/environment/industry/stationary/ied/legislation.htm. The main principles include:

- an integrated approach;
- best available technologies (BATs);

- flexibility;
- inspections; and
- public participation.

The binding emission limits in IED are based on what the BATs can achieve. BAT conclusions set out what BAT should be for a particular sector and give a set of associated emission levels (BAT-AELs). The BATs and BAT-AELs are defined in BAT reference documents (BREF). The member states permit writers in the relevant authorities have to set emission limit values (ELVs) on the basis of BAT-AELs to ensure full compliance with the LCP BREF.

Chapter III (with Annex V) of the IED sets out special provisions for certain pollutant emissions from combustion plants with a total rated thermal input equal to or greater than 50 MW, irrespective of the type of fuel used. The new ELVs set by IED for large combustion plants are more stringent than the values set within the old LCPD. These legislated ELVs are valid from 7 January 2014 for new installations and retrofitted plants and from 1 January 2016 for existing installations. However, during the interim period, individual member states can introduce a Transitional National Plan (TNP) for existing plants to ease the transition. There is still no specific limit for $PM_{2.5}$ from coal-fired power plant, just an overall PM (dust) limit. Table 10 lists ELVs from the IED for dust, SO_2 and NOx from existing coal- and lignite-fired power plants, and Table 11 does the same for new and retrofitted power plants. Existing plants refer to installations where their permit was granted before 7 January 2013 or the operator of which had submitted a complete application prior to this date and such plants were put into operation no later than 7 January 2014. New plants refer to installations entering into operation after 7 January 2014. Retrofitted plants refer to those plants which had been granted an exemption by Directive 2001/80/EC, but had been retrofitted and would be in operation after 1 January 2016. The concentrations of dust, SO_2, and NOx have to be measured *continuously*. All ELVs are calculated at a temperature of 0°C, 101.325 kPa and on a dry flue gas basis with 6% of O_2 (European Commission, 2010, European Commission, 2001).

Table 10 ELVs from IED (2010/75/EU) for NOx, SO_2 and dust from existing coal and lignite combustion plants (European Commission, 2010)

Total rated thermal input, MW	ELV, mg/m^3		
	NOx	SO_2	Dust
50–100	300[1]	400	30
100–300	200	250	25
>300	200	200	20

[1] 450 mg/m^3 in case of pulverised lignite combustion.

Notes:

Combustion plants using solid fuels put into operation no later than 27 November 2003, and which do not operate more than 1500 operating hours per year as a rolling average over a period of 5 years, shall be subject to an ELV for SO_2 of 800 mg/m^3.

Combustion plants using solid fuels, with a total rated thermal input not exceeding 500 MW, put into operation no later than 27 November 2003, and which do not operate more than 1500 operating hours per year as a rolling average over a period of 5 years, shall be subject to an ELV for NOx of 450 mg/m^3.

Combustion plants using solid fuels with a total rated thermal input greater than 500 MW, which were granted a permit before 1 July 1987 and which do not operate more than 1500 operating hours per year as a rolling average over a period of 5 years, shall be subject to an ELV for NOx of 450 mg/m^3.

Table 11 ELVs from IED (2010/75/EU) for NOx, SO_2 and dust from new and retrofitted coal and lignite combustion plants (European Commission, 2010)

Total rated thermal input, MW	ELV, mg/m³		
	NOx	SO_2	Dust
50–100	300[1]	400	20
100–300	200	200	20
>300	150[2]	150[3]	10

[1] 400 mg/m³ in case of pulverised lignite combustion.

[2] 200 mg/m³ in case of pulverised lignite combustion.

[3] 200 mg/m³ in case of circulating or pressurised fluidised bed combustion.

The IED allows combustion plants firing indigenous solid fuel that cannot comply with the ELVs for SO_2 due to the characteristics of the fuel, to instead apply the minimum rates of desulphurisation, given in Table 12.

Table 12 Minimum rate of desulphurisation from IED (2010/75/EU) for combustion plants (European Commission, 2010)

Total rated thermal input, MW	Minimum rate of desulphurisation, %		
	Existing and in operation prior to 2003[1]	Other existing	New and retrofitted
50–100	80	92	93
100–300	90	92	93
>300	96	96	97

[1] Plants which were granted a permit before 27 November 2002 or the operators of which had submitted a complete application for a permit before that date, provided that the plant was put into operation no later than 27 November 2003.

The standards in the LCP BREF are scheduled to be revised every eight years. The latest one was published in 2006 which was two years behind the update schedule. The updating process started in 2011 and a draft updated LCP BREF was published in July 2013 (European IPPC Bureau, 2016). In April 2015, the EC's IPPC Bureau released a new draft LCP BREF for the technical working group to discuss. EU member states were expected to vote on the proposal by the end of 2015, followed by formal adoption in January 2016. The new ELVs in the LCP BREF are expected to be implemented by member states between January 2016 and January 2020. By the end of this period, new ELVs need to be applied at the plant level. One significant change in the new draft is that the BAT-ELVs are to be measured by yearly average and daily average (averaged over the sampling period) rather than continuously. It also creates a new power plant thermal capacity category of 1000 MW for dust emissions. Tables 13, 14, 15 list the BAT-AELs for NOx, SO_2 and dust, respectively for coal- and lignite-fired power plants taken from the new draft LCP BREF downloaded from the Ministry of Environment of Poland website: http://ippc.mos.gov.pl/ippc/custom/LCPBATconclusionsfinal(1).pdf. The definition for 'new plant' is a combustion plant first permitted (pursuant to the provisions in Articles 4 and 5 of Directive 2010/75/EU) at the installation, or a complete replacement of a combustion plant on the existing foundations of the installation after the publication of the new LCP BREF. 'Existing plant' refers to a combustion plant which is not a new plant.

Table 13 NOx emission BAT-ELVs from the draft LCP BREF (European IPPC Bureau, 2016)

Total rated thermal input, MW	Annual average[1], mg/m^3		Daily average or average over the sampling period, mg/m^3	
	New plants	Existing plants[1]	New plants	Existing plants
<100	100–150	100–270	155–200	165–330
100–300	50–100	100–180	80–130	155–210
≥300 FBC boiler firing coal and/or lignite and lignite-fired PC boiler	50–85	85–150	80–125	140–165
≥300 coal-fired PC boiler	65–85	65–150	80–125	200[2]

[1] These BAT-ELVs do not apply when plants operate at <1500 h/y.

[2] In the case of plants put into operation no later than 7 January 2014, the higher end of the range is 200 mg/m^3.

Table 14 SO$_2$ emission BAT-ELVs from the draft LCP BREF (European IPPC Bureau, 2016)

Total rated thermal input, MW	Annual average[1], mg/Nm^3		Daily average for new plants, mg/m^3	Daily average or average over the sampling period for existing plants, mg/m^3
	New plants	Existing plants[1]		
<100	150–200	150–360	170–220	170–400
100–300	80–150	80–200	135–200	135–220
≥300 PC boiler	10–75	10–130	25–110	25–165[2]
≥300 FBC boiler[3]	20–75	20–180	25–110	50–220

[1] These BAT-ELVs do not apply to plants operated at <1500 h/y.

[2] The higher end of the BAT-AEL range is 220 mg/m^3 in the case of plants operated in peak or emergency load modes.

[3] For circulating fluidised bed boilers, the lower end of the range can be achieved by using a high efficiency wet FGD system. The higher end of the range can be achieved by using boiler in-bed sorbent injection.

Table 15 Dust emission BAT-ELVs from the draft LCP BREF (European IPPC Bureau, 2016)

Total rated thermal input, MW	Annual average, mg/m^3		Daily average or average over the sampling period, mg/m^3	
	New plants	Existing plants	New plants	Existing plants
100–300	2–5	2–14	3–15	4–22
300–1000	2–5	2–10	3–10	3–11
≥1000	2–5	2–8	3–10	3–11

These BAT-ELVs do not apply to plants operated at <1500 h/y.

At the time of writing this report (February 2016), the draft LCP BREF is still under discussion. The European Environmental Bureau thinks that the standards are set at too low a level and will constitute a lowering of environmental standards in force in the 2006 LCP BREF for existing large coal- or lignite-fired power plants (Wates, 2015). However, some think that the new ELVs are stricter than the old ones (Flynn, 2015; Ottery, 2015). This means that coal plant operators will have to invest in technologies to clean up their emissions. For instance, as ENDS Europe reported, the Czech Republic has warned that the draft BREF could have a severe economic impact on some countries, with particular concern over the BAT associated emission levels for SOx on lignite-fired power plants. The Polish energy lobby group has also recently voiced its strong concerns that the LCP BREF will cost the Polish power sector almost €5 billion to update its ageing coal-burning fleet – with NOx and SO_2 emissions the main areas of dispute (Flynn, 2015).

2.4 Germany

Germany is a member state of the European Union and is therefore bound by the emission legislation summarised in Section 2.3. Its air quality and energy related policies are created and managed by the Federal Ministry for Environment, Nature Conservation and Nuclear Safety and revolve around the *Federal Immission Control Act*. Following the initial enforcement in 1974, there have been many multiple amendments and ordinances to the Act, affecting a wider range of industries. In May 2013, the regulations for the implementation of the EU Industrial Emissions Directive (2010/75/EU) came into force. These contain rules on authorisation, operation, closure and monitoring of industrial plants. Approximately 9,000 units are affected (IEA CCC, 2014; Infozentrum UmweltWirtschaft, 2013). To meet the requirements of European law the following EU legislation has been transposed and enacted into German law:

1. National Emission Ceilings for Certain Atmospheric Pollutants Directive (NECD - 2001/81/EC) via the 39 BlmSchV, Regulation on ambient air quality standards and emission ceilings.
2. Regulations for the implementation of the EU directive of the European Parliament and the Council on Industrial Emissions (Integrated Pollution Prevention and Control) (Recast) (2010/75/EU) has been transposed and separated into three parts, a legislative Act and two regulations:
    i. Act for the Implementation of the Directive on Industrial Emissions from 8 April 2013, published in Bundesgesetzblatt Teil I 2013 Nr, 17 vom 12.04.2013 pg 734-752;
    ii. Regulation to Implement the Directive on Industrial Emissions, Amending the Regulations on Pollution Control and Fault Advisor Ordinance and adopting the Decree from 2 May 2013, published in Bundesgesetzblatt Teil I 2013 No, 21 vom 02.05.2013 pg 973-1020.
3. Large Combustion Plant Directive (LCPD – 2001/80/EC) via 13 BImSchV, Ordinance on Large Combustion Plants, Gas Turbines and Internal Combustion Engine Systems.

Power plants with a thermal input greater than 50 MW are regulated by the *13 BImSchV, Ordinance on Large Combustion Plants, Gas Turbines and Internal Combustion Engine Systems* (*see* Table 16) for new plants and Table 17 for existing plants). This document was updated recently, on 31 August 2015. New plants are those built after 7 January 2014. Existing plants refer to plants which were in operation before 7 January 2014 or had a license granted before 7 January 2013 and were in operation after 7 January 2014. By 31 December 2012, plants which did not meet the regulation had to close. All of the above emission limit values are obtained at 0°C and 101.3 kPa at 6% O_2 in flue gas.

Table 16 German ELVs for NOx, SO_2 and PM for new coal-fired power plants with thermal input greater than 50 MW (IEA CCC, 2015)

Pollutants	Plant size, MWth	ELV, mg/m^3		
		24 hours	Half hourly	Annual
NOx[1](as NO_2)	50–100	300 (400 pulverised lignite)	600 (800 pulverised lignite)	250
	100–300	200	400	100
	>300	150 (200 pulverised lignite)	300 (400 pulverised lignite)	100
SOx[2] (as SO_2)	50–100	400[3] (350[4] fluidised bed)	800[3] (700[4] fluidised bed)	
	100–300	200[5]	400[5]	
	>300	150 (200 circulating or pressurised fluidised bed)[6]	300 (400 circulating or pressurised fluidised bed)[6]	
Dust	all	10	20	10 (>300 MWth)

[1] NOx includes NO and NO_2.

[2] SOx includes SO_2 and SO_3.

[3] An alternative desulphurisation rate of 93% must be achieved if the stated ELV cannot be met by reasonable effort due to the sulphur content of the indigenous fuels.

[4] A desulphurisation rate of at least 75% must also be achieved.

[5] A desulphurisation rate of at least 85% must also be achieved. An ELV value of 300 mg/m^3 for the daily mean value and 600 mg/m^3 for the half-hourly mean value shall apply and additionally a desulphurisation rate of at least 93% of the daily mean value must be achieved, if the stated daily and half-hourly mean ELV cannot be met by reasonable effort due to the sulphur content of the indigenous fuels.

[6] A desulphurisation rate of at least 85% must also be achieved. An ELV of 400 mg/m^3 for the daily mean value and 800 mg/m^3 for the half-hourly mean value applies and additionally a desulphurisation rate of at least 97% of the daily mean value must be achieved, if the stated daily and half-hourly mean ELV cannot be met by reasonable effort due to the sulphur content of the indigenous fuels.

Table 17 German ELVs for NOx, SO$_2$ and PM for existing coal-fired power plants with thermal input greater than 50 MW (IEA CCC, 2015)

Pollutants	**Plant size, MWth**	**ELV, mg/m^3**		
		24 hours	**Half hourly**	**Annual**
NOx[1]	50–100	300[3] (450 pulverised lignite)	600[3] (900 pulverised lignite)	
	100–300	200[4]	400[4]	
	>300	200	400	
SOx[2]	50–100[5]	400[6] (350[7] fluidised bed)	800[6] (700[7] fluidised bed)	
	100–300	200[8]	400[8]	
	>300	200[9]	400[9]	
Dust	all	20	40	10 (>300 MWth)

[1] NOx includes NO and NO$_2$.

[2] SOx includes SO$_2$ and SO$_3$.

[3] For plants which do not operate for more than 1500 operating hours per year as a rolling average over a period of 5 years, an ELV of 450 mg/m^3 for the daily mean value and 900 mg/m^3 for the half-hourly average must be achieved.

[4] For plants which do not operate for more than 1500 operating hours per year as a rolling average over a period of 5 years, an ELV of 400 mg/m^3 for the daily mean value and 800 mg/m^3 for the half-hourly average must be achieved.

[5] An alternative desulphurisation rate of at least 92% of the daily mean value must be achieved if the stated ELV cannot be met by reasonable effort due to the sulphur content of the indigenous fuels.

[6] For plants which do not operate for more than 1500 operating hours per year as a rolling average over a period of 5 years, an ELV of 800 mg/m^3 for the daily mean value and 1600 mg/m^3 for the half-hourly average must be achieved.

[7] A desulphurisation rate of at least 75% must be achieved.

[8] A desulphurisation rate of at least 75% for fluidised bed combustion and at least 60% for other combustion types must also be achieved. For plants (except fluidised bed combustion) which do not operate for more than 1500 operating hours per year as a rolling average over a period of 5 years, an ELV of 800 mg/m^3 for the daily mean value and of 1600 mg/m^3 for the half-hourly average must be achieved. The requirements for the rate of desulphurisation remain unaffected. An ELV of 300 mg/m^3 for the daily mean value and 600 mg/m^3 for the half-hourly mean value applies and additionally a desulphurisation rate of at least 92% of the daily mean value must be achieved, if the stated daily and half-hourly mean ELV cannot be met by reasonable effort due to the sulphur content of the indigenous fuels.

[9] A desulphurisation rate of at least 85% must also be achieved. For plants which do not operate for more than 1500 operating hours per year as a rolling average over a period of 5 years, an emission limit value of 300 mg/m^3 for the daily mean value and 600 mg/m^3 for the half-hourly average must be achieved. The requirements for the rate of desulphurisation remain unaffected. An ELV of 400 mg/m^3 for the daily mean value and 800 mg/m^3 for the half-hourly mean value shall apply and additionally a desulphurisation rate of at least 96% of the daily mean value must be achieved, if the stated daily and half-hourly mean ELV cannot be met by reasonable effort due to the sulphur content of the indigenous fuels.

2.5 India

The Indian national ambient air quality standards were implemented in 2009 by the Central Pollution Control Board (CPCB), a division of the Ministry of Environment and Forests (Indian CPCB, 2009). Compared to those of the WHO and EU, the Indian PM$_{2.5}$ standard is less strict (60 μg/m^3 for 24 hours and 40 μg/m^3 for annual) but the NOx and SO$_2$ standards are in line. According to the *Environment (Protection) Act, 1986* (Ministry of Environment and Forests, 1986), the CPCB set the *Standards for emission or discharge of environmental pollutants from various industries*, which covers particulate matter from thermal power plants (Indian CPCB, 2015). The PM emission limit is 150 mg/m^3 for power plants with a capacity of equal or greater than 210 MW and 350 mg/m^3 for those smaller than 210 MW. There are no emission limits for SO$_2$ and NOx. However, minimum stack heights are specified in order to disperse sulphur dioxide. New emission standards for coal-fired power plants are currently being debated (*see* Table 18).

Table 18 Emission standards for NO_2, SO_2 and PM from Indian coal-fired power plants (Muthukrishnan, 2015)

Pollutants	ELV, mg/m^3		
	Plants installed before 2003	Plants installed between 2003 and 2016	Plants installed after January 2017
NOx	600	300	100
SO_2	600 (<500MW)	200 (≥500MW)	100
PM	100	50	30

2.6 Indonesia

In the national ambient air quality standards for Indonesia, PM is measured as total suspended particulate (TSP). The annual measurement for TSP is 90 µg/m^3, which is very high compared to 10 µg/m^3 for the WHO (even though it is for $PM_{2.5}$). The NOx and SO_2 standards (24 hours average 150 µg/m^3 and 365 µg/m^3 respectively) are also weak compared to the WHO and EU. Emission standards for stationary sources, including coal-fired power plants, were first introduced by the Ministry of Environment (MOE) in 1988 and were updated in 1995 and 2008 (*see* Table 19). Existing power plants and those in development before the decree was issued should comply with the 1995 standards. The standards for new power plants are stricter and those under construction before 1 January 2015 have to comply with the 2008 standards. Power plants must meet these emission standards 95% of the time over 3 months. The reference conditions are different from some other countries being 25°C at 101.3kPa on a dry flue gas with 7% of O_2 in the flue gas.

Table 19 Emission standards for SO_2, NOx and PM for Indonesian coal-fired power plants (IEACCC, 2015)

Power plant	SO_2, mg/m^3	NOx (as NO_2), mg/m^3	PM, mg/m^3
Old coal-fired power plants and those in development before enactment	750	850	150
New coal-fired power plants and those under construction before enactment by 1 January 2015	750	750	100

2.7 Japan

Formed in 2001 the Ministry of the Environment (MOE) in Japan is responsible for establishing and implementing environmental policy, regulations on air pollution control, monitoring and management, setting up the basic environmental plan, the regional environmental pollution control programme, and so on. The *Basic Environment Law* was enacted in November 1993. In December 1994, an action plan called the *Basic Environment Plan* was adopted. The plan systematically clarifies the measures to be taken by national and local governments, as well as actions to be carried out by citizens, businesses and private organisations. It also defines the roles of parties involved, and the ways and means for effectively pursuing environmental policies. The Air Quality Standards have been amended over the years, and the current standard for $PM_{2.5}$ is 35 µg/m^3 for 24 hours and 15 µg/m^3 for annual. NOx and SO_2 are measured in ppm and are in line with the WHO guidelines (Japan MOE, 2015a).

The emission standards for coal-fired power plants are given in the *Regulatory measures against air pollutants emitted from factories and business sites and the outline of regulation* (Japan MOE, 2015b). All ELVs are calculated at a temperature of 0°C, and a pressure of 101.3 kPa. For soot and dust, there is a general standard and a special standard. General standards are national standards that apply to existing plants. Special standards are tighter and apply to new plants in the defined areas (*see* Table 20). According to Myllyvirta (2015), the best performing power plants in Japan can achieve emissions of 4–5 mg/m^3 for PM.

Table 20 Emission standards for soot and dust emission from coal boilers (Japan MOE, 2015b)

Capacity, m^3/h	General standard, mg/m^3	Special standard, mg/m^3
≥200,000	100	50
40,000–200,000	200	100
<40,000	300	150
Heating area:10 m^2 or above		

The same NOx ELVs apply to both existing and new power plants as below (the NOx ELVs have been converted into mg/m^3 for comparison purposes):

Capacity, m^3/h	Emission standard, mg/m^3
≥700,000	410 (200 ppm)
40,000–700,000	513 (250 ppm)
<40,000	614 (300 ppm)

The Japanese emission standard for sulphur oxides is more complicated. The allowable discharge amount of sulphur oxides (as SO_2) depends on the area in which the plant is situated, and is calculated according to the following equation:

$$q = K \times 10^{-3} \times He^2$$

where: *q* is the permissible hourly emission volume of sulphur oxides (m^3/h); *He* is the effective height (in metres) of the stack and equals the sum of the actual height of the stack and the smoke (exhaust gas) ascent height; and *K* is a constant - its value varies according to the region where the plant is located.

The advantage of this standard is that it allows more stringent regulations in vulnerable areas by making *K* smaller. Limits on the total amount of SO_2 are also set for each area and/or plant based on the total emission reduction plan. The *K* values are listed at the MOE website: https://www.env.go.jp/en/air/aq/air/air3_table.html.

2.8 South Africa

The South African *National Environmental Management Air Quality Act (No. 39 of 2004)* was issued in February 2005 (South Africa, 2005). It mandates the norms, standards, mechanisms, systems and procedures for air quality improvement. It also establishes the national framework within which these standards will be created, giving the Minister of Environmental Affairs or the members of the Executive Council of a province (MEC) the authority to issue standards, enforce regulations and other measures and implement penalties for noncompliance, and establish 'funding arrangements'. Schedule 2 of the *Act* No. 39 of 2004 gave the ambient air quality standards. It was repealed in the *Act No. 20 of 2014: National Environmental Management: Air Quality Amendment Act, 2014* (South Africa, 2014). But no report can be found mentioning the repeal of the *National Ambient Air Quality Standard for Particulate Matter of Aerodynamic Diameter Less Than 2.5 Micron Metre ($PM_{2.5}$)* (*see* Table 21) which was issued by the Department of Environment Affairs (DEA) in June 2012 (DEA, 2012a).

Table 21 South African AAQS for $PM_{2.5}$ (DEA, 2012a)

Averaging time	ELV, µg/m^3	Frequency of exceedance	Compliance date
24 hours	65	4	Immediate – 31 December 2015
	40		1 January 2016 – 31 December 2029
	25		1 Jan 2030
1 year	25	0	Immediate – 31 December 2015
	20		1 January 2016 – 31 December 2029
	15		1 January 2030
ELV is expressed at 25°C and 101.3 kPa			

Under Act No. 39 of 2004, the Department of Environmental Affairs set up regulations relating to *Listed Activities and Associated Minimum Emission Standards* in which the emission limit values for combustion plants with a thermal input greater than 50 MW are included (*see* Table 22). The *Minimum Emission Standards* were first issued in 2010, and then amended in November 2012 (South Africa DEA, 2012b). The standards apply to both permanently operated plants and experimental (pilot) plants. New plants in the standards refer to plants that applied for authorisation on or after 1 April 2010, while existing plants are those operating or that had applied for authorisation before 1 April 2010. New plants had to comply with the standards as soon as they were issued. Existing plants had until 1 April 2015 to comply, but have to meet the emission standards for new plants by 1 April 2020 (DEA, 2015b). However, these compliance timeframes have been postponed because industries felt the standards were too strict to be met by the 2015 deadline.

Table 22 South African emission standards for solid fuel combustion installations (DEA, 2012b)

Pollutant	**ELV, mg/m^3**	
	New plants	**Existing plants**
NO_x (as NO_2)	750	1100
SO_2	500	3500
PM	50	100
Continuous monitoring under reference conditions of 0°C, 101.3 kPa and dry flue gas basis with 10% of O_2		

2.9 Thailand

The ambient air quality standards for Thailand have separate values for $PM_{2.5}$, PM_{10}, and total suspended particulates. The $PM_{2.5}$ value for Thailand is the same as the EU's but the standards for NOx (320 μg/m³ for 1 hour and 57 μg/m³ for annual) and SO_2 (780 μg/m³ for 1 hour and 300 μg/m³ for 24 hours) are weaker (Thailand PCD, 2015).

In Thailand, emission standards are set by the Pollution Control Department of the Ministry of Natural Resources and Environment under the authority of the *Enhancement and Conservation of National Environmental Act, B.E. 2535 (1992)*. Emission limits for new power plants operating after 5 January 2010 were published in the *Royal Thai Government Gazette* (volume 127, section 7D on 15 Jan 2010). New power plants refer to plants generating, transmitting or distributing electricity that acquired a permit for operation or expansion after 15 January 2010. Emission standards for existing power plants are also covered in the *Royal Thai Government Gazette* (volume 121, section 113D, 7 Oct 2004), with special mention of the Mae Moh power plant (*see* Table 23). Units 4-7 of the Mae Moh power plant are going to be replaced by a single ultra-supercritical unit, which is planned to be operational in 2019. The ELVs are calculated at 25°C at 101.3kPa on a dry flue gas base, with 50% of excess air or 7% of O_2 during combustion (IEA CCC, 2015).

Table 23 Emission standards for NOx, SO_2 and PM for coal-fired power plants in Thailand (IEA CCC, 2015)

Power plant, MW	**NOx (as NO_2), mg/m³ (ppm)**	**SO_2,mg/m³ (ppm)**	**PM, mg/m³**
New power plants			
≤50	410 (200)	1030 (360)	80
>50	410 (200)	515 (180)	80
Existing power plants			
Mae Moh units 4–7 (4 x 150) and units 8–13 (6 x 300)	1025 (500)	915 (320)	180
Other coal-fired plants of any size	820 (400)	2002 (700)	180

2.10 USA

The USA was the first country in the world to start regulating $PM_{2.5}$. The air pollution control systems are quite comprehensive; hence they will be discussed in detail. The Clean Air Act (CAA) of 1963 and its 1970 amendments form the basis for air pollution control legislation in the United States, authorising the development of federal and state regulations to limit emissions from industrial sources and transportation. The CAA requires the US Environmental Protection Agency (EPA) to set National Ambient Air Quality Standards (NAAQS) for ambient levels of a range of pollutants (including particulate matter, SO_2, NOx, carbon monoxide, ozone, and lead), as well as emissions limits known as New Source Performance Standards (NSPS) for new industrial sources of pollutants, such as coal plants.

Following a 1997 revision of the CAA in which the EPA issued the final $PM_{2.5}$ NAAQS, further regulation of new sources was introduced based on whether the NAAQS were met within their administrative region. For 'attainment areas', a ruling for Prevention of Significant Deterioration (PSD) of the air quality requires that the best available control technology (BACT) be implemented for new sources, while those in 'non-attainment areas' are subject to the more stringent 'lowest achievable emissions rate' (LAER). These are case-by-case assessments which essentially use the NSPS as baseline emissions limits, but usually require much higher levels of abatement. A BACT assessment will determine the maximum degree of control that can be achieved by a source within reasonable energetic and economic bounds, whether by abatement technology or process changes such as fuel switching. This is based on analysis of emissions already achieved by existing plants within the same category (for example pulverised coal plant). For LAER, a strict limit is imposed without consideration of the economic or energetic penalty to the plant, and emissions must often be offset against other emissions reductions in the region. These assessments, known collectively as New Source Reviews, are generally conducted at the state level as part of State Implementation Plans (SIP) for achieving and maintaining the NAAQS. These plans may also include limits on plants built before 1971 that are exempt from the NSPS.

For PM, the first rules were promulgated in 1971 under the CAA. Since then, the PM standards have been updated continually as the law requires EPA to periodically review them to ensure that they provide adequate health and environmental protection. The development history of the NAAQS for PM during the period 1971-2012 is given in Table 24. In December 2012, the EPA strengthened the primary annual NAAQS for $PM_{2.5}$ by setting the standard at 12 $\mu g/m^3$, replacing the previous standard of 15 $\mu g/m^3$, which was set in 1997. The EPA retained the previous annual secondary standards at 15 $\mu g/m^3$. The Agency also retained the primary and secondary 24-hour standard at 35 $\mu g/m^3$.

Table 24 History of the NAAQS for particulate matter (EPA, 2015a)

Final rule	Primary/ secondary	Indicator	Averaging time	Level, $\mu g/m^3$	Form
1971 36 FR 8186 30 April 1971	Primary	TSP[1]	24 hours	260	Not to be exceeded more than once per year
			annual	75	Annual geometric mean
	Secondary	TSP	24 hours	150	Not to be exceeded more than once per year
			annual	60	Annual geometric mean
1987 52 FR 24634 1 July 1987	Primary and secondary	PM_{10}	24 hours	150	Not to be exceeded more than once per year on average over a 3-year period
			annual	50	Annual arithmetic mean, averaged over 3 years
1997 62 FR 38652 18 July 1997	Primary and secondary	$PM_{2.5}$	24 hours	65	98th percentile, averaged over 3 years
			annual	15.0	Annual arithmetic mean, averaged over 3 years[2, 3]
		PM_{10}	24 hours	150	Initially promulgated 99th percentile, averaged over 3 years; when 1997 standards for PM_{10} were vacated, the form of 1987 standards remained in place (not to be exceeded more than once per year on average over a 3-year period)
			annual	50	Annual arithmetic mean, averaged over 3 years
2006 71 FR 61144 17 Oct 2006	Primary and secondary	$PM_{2.5}$	24 hours	35	98th percentile, averaged over 3 years[4]
			annual	15.0	Annual arithmetic mean, averaged over 3 years[5]
		PM_{10}	24 hours[6]	150	Not to be exceeded more than once per year on average over a 3-year period
2012	Primary	$PM_{2.5}$	annual	12.0	Annual arithmetic mean, averaged over 3 years
	Secondary		annual	15.0	Annual arithmetic mean, averaged over 3 years
	Primary and secondary		24 hours	35	98th percentile, averaged over 3 years
	Primary and secondary	PM_{10}	24 hours[6]	150	Not to be exceeded more than once per year on average over a 3-year period

[1] TSP = total suspended particles.

[2] The level of the annual standard is defined to one decimal place (that is 15.0 $\mu g/m^3$) as determined by rounding.

[3] The level of the standard was to be compared to measurements made at sites that represent 'community-wide air quality' recording the highest level, or, if specific requirements were satisfied, to average measurements from multiple community-wide air quality monitoring sites ('spatial averaging').

[4] The level of the 24-hour standard is defined as an integer (zero decimal places) as determined by rounding.

[5] EPA tightened the constraints on the spatial averaging criteria by further limiting the conditions under which some areas may average measurements from multiple community-oriented monitors to determine compliance.

[6] EPA revoked the annual PM_{10} NAAQS in 2006.

After taking the important step on $PM_{2.5}$ regulation in 2012, the EPA proposed a rule in November 2013 to clarify $PM_{2.5}$ implementation requirements to the states for 1997 and 2006 non-attainment areas. In April 2014, EPA classified as 'moderate' non-attainment areas for the 1997 and 2006 fine particle pollution standards and set 31 December 2014 as the deadline for states to submit remaining implementation plan requirements. In March 2015, EPA proposed requirements for implementing the NAAQS for $PM_{2.5}$ in areas that were designated non-attainment for these standards. These requirements would apply to current and future fine particle pollution standards (EPA, 2015b). The new $PM_{2.5}$ standard could lead to further reductions in NOx and SO_2 emissions. Current NAAQS for NOx and SO_2 are listed in Table 25. The states would have until 2020 to meet the 2012 revised annual $PM_{2.5}$ standards.

Table 25 EPA current NAAQS for SO_2 and NOx (EPA, 2015a)

Final rule	Primary/ secondary	Averaging time	Level	Form
NOx [75 FR 6474, 9 Feb 2010] [61 FR 52852, 8 Oct 1996]	primary	1 hour	100 ppb	98th percentile of 1-hour daily maximum concentrations, averaged over 3 years
	primary and secondary	annual	53 ppb[1]	Annual mean
SO_2 [75 FR 35520, 22 Jun 2010] [38 FR 25678, 14 Sept 1973]	primary	1 hour	75 ppb[2]	99th percentile of 1-hour daily maximum concentrations, averaged over 3 years
	secondary	3 hours	0.5 ppm	Not to be exceeded more than once per year

[1] The official level of the annual NO_2 standard is 0.053 ppm, equal to 53 ppb, which is shown here for the purpose of clearer comparison to the 1 hour standard.

[2] Final rule signed 2 June 2010. The 1971 annual and 24 hour SO_2 standards were also revoked in that same rulemaking. However, these standards remain in effect until one year after an area is designated for the 2010 standard, except in areas designated non-attainment for the 1971 standards, where the 1971 standards remain in effect until implementation plans to attain or maintain the 2010 standard are approved.

The NSPS have applied to all coal plants constructed, reconstructed, or significantly modified since September 1971, and have become progressively more stringent since their first incarnation, with the most recent revision applying to plants constructed after May 2011 (*see* Table 26). The NSPS are determined under ISO conditions (namely temperature of 0°C, a relative humidity of 60%, and a pressure of 101.3 kPa and average over a 24-hour period). Significantly, since 1978 the standards have required a percentage reduction of SO_2 emissions from unabated levels in addition to an absolute limit. The EPA generally concentrates on enforcing the stricter, latter regulation.

Table 26 NSPS for coal-fired power plant (IEACCC, 2014)

Plant age	**NOx**	**SO_2**	**Particulate matter (PM)**
1971 – 1978	300 ng/J heat input	520 ng/J heat input	43 ng/J heat input
Sep 1978–1997	**Subbituminous:** 210 ng/J heat input; Other coal types*: 260 ng/J heat input	520 ng/J heat input and 90% reduction (or 70% reduction where <260 ng/J); 180 ng/J gross output; 65 ng/J heat input	13 ng/J heat input
1978 – March 2005	**New plant**: 200 ng/J gross output; Reconstructed: 65 ng/J heat input		
Commenced construction: March 2005 – May 2011	130 ng/J gross output; 95% reduction	180 ng/J gross output	18 ng/J gross output; 6.4 ng/J heat input. Or: 13 ng/J input and 99.9% reduction
Commenced reconstruction: March 2005 – May 2011	130 ng/J gross output; 47 ng/J heat input; 95% reduction	180 ng/J gross output; 65 ng/J heat input	
Modified: March 2005 – May 2011	180 ng/J gross output; 65 ng/J heat input; 90% reduction	180 ng/J gross output; 65 ng/J heat input	18 ng/J gross output; 6.4 ng/J heat input. Or: 13 ng/J input and 99.8% reduction
Construction or reconstruction after: 3 May 2011	88 ng/J gross output; 95 ng/J net output	130 ng/J gross output; 140 ng/J net output; 97% reduction	11 ng/J gross output; 12 ng/J net input
Modified after: 3 May 2011	140 ng/J gross output	180 ng/J gross output; 90% reduction	18 ng/J gross output; 6.4 ng/J heat input. Or: 13 ng/J input and 99.8% reduction

* except slag tap furnaces firing more than 25% lignite mined in North Dakota, South Dakota, or Montana (340 ng/J)

PM standard exceptions: Plant constructed before 2005 and without continuous emissions monitoring can meet an opacity limit of 20% (including 6 min/h of 27%).

NOx standard exceptions: Plant firing >75% coal refuse is exempt from NOx limits if constructed before 1997, and limits of 110 ng/J gross output and 120 ng/J net output apply if constructed after May 2011. For IGCC constructed 2005–2011, 130 ng/J gross output applies. Plant constructed after May 2011 can chose to meet alternative combined NOx and CO limits of 140 ng/J gross output and 150 ng/J net output.

SO_2 standard exceptions: Plant using solid-solvent refined coal (520 ng/J and 85% reduction). Plant using 100% anthracite, classified as a resource recovery unit, or in a non-continental area (520 ng/J). Plant firing ≥75% coal refuse and, constructed since March 2005 (180 ng/J gross output, 94% reduction), reconstructed since March 2005 (180 ng/J gross output, 65 ng/J input, 94% reduction), modified since March 2005 (180 ng/J gross output, 65 ng/J input, 90% reduction).

A major amendment to the CAA in 1990 included the Acid Rain Program (ARP) aimed at significantly reducing SO_2 and NOx emissions from existing emitters through a cap-and-trade system. The first phase of this programme ran from 1995 to 1999 and applied to 110 major sources. Allocated emissions allowances were based on an emission rate of 2.5 lb/MBtu of SO_2 and a plant's average fuel consumption in the base year, and were aimed at achieving an annual cap of 8.95 Mt/y (EPA, 2015c). A second phase from 2000 expanded the programme to all fossil fuel-fired boilers over 75 MWe and based allowances on 1.2 lb/MBtu SO_2. NOx emissions for coal-fired boilers were limited to:

tangentially-fired	0.40 lb/Mbtu	dry bottom wall-fired	0.46 lb/Mbtu
cell burners	0.68 lb/Mbtu	wet bottom	0.84 lb/Mbtu
cyclones	0.86 lb/Mbtu	verticals	0.80 lb/Mbtu

The CAA's 'good neighbour' provision requires the EPA and the states to address interstate transport of air pollution that affects downwind states' ability to attain and maintain the NAAQS. The EPA has administered the NO_X Budget Trading Program (NBP), the Clean Air Interstate Rule (CAIR), and the Cross-State Air Pollution Rule (CSAPR). The NBP was a cap-and-trade programme created to reduce the regional transport of NOx emissions from power plants and other large combustion sources in the eastern USA. The NBP began in 2003 and was designed to reduce emissions during the warm summer months, referred to as the ozone season, when ground level ozone concentrations are highest. It was a central component of the NOx SIP Call, promulgated in 1998. From the beginning of its implementation in 2003 to 2008, the NBP dramatically reduced NOx emissions from power plants and industrial sources during the summer months, contributing significantly to improvements in levels of ozone in air quality. Beginning in 2009, the NBP was effectively replaced by the ozone season NOx programme under the CAIR, which required further summertime NOx reductions from the power sector (EPA, 2015d).

CAIR is a variant on the cap-and-trade system introduced in 2005 to respond to the fact that emissions can also contribute to NAAQS violations in states downwind of the emitting source. It essentially lowered the SO_2 cap for 27 states and the District of Columbia by 70% by requiring three SO_2 allowances in place of one. Although finally implemented in 2008, legal proceedings by states and utilities have led the EPA to propose the CSAPR as its replacement. The CSAPR was finalised by the EPA in July 2011 but vacated by the US Court of Appeals for the District of Columbia (D.C.) Circuit in 2012. The EPA appealed the decision to the Supreme Court, which reversed the D.C. Circuit's decision in April 2014. CSAPR has been reinstated and the EPA began to implement the Phase 1 SO_2 and NOx requirements in January 2015. Phase 2 will begin in 2017. However, on 28 July 2015, a ruling by the D.C. Circuit Court ordered the EPA to redo the overly strict SO_2 and NOx standards for 13 upwind states, mostly in the South and Midwest. Texas and South Carolina would see limits for both forms of pollution adjusted, while new limits for either SO_2 or NOx would be set in 11 other states. In addition, the EPA proposed Federal Implementation Plans (FIPs) requiring more stringent SO_2 emission requirements for coal-fired power plants.

2.11 Comments

$PM_{2.5}$ is made up of primary and secondary $PM_{2.5}$. Secondary $PM_{2.5}$ is formed from SOx, NOx, VOC and ammonia that react chemically in the air. There is no a method yet to calculate or model secondary $PM_{2.5}$ other than using SOx and NOx as surrogates. However, the impacts of SO_2 and NOx controls on $PM_{2.5}$ reduction are nonlinear and are dependent on location, magnitude, season, temperature and other factors.

All of the countries discussed in this chapter, apart from Indonesia, have regulated $PM_{2.5}$ in their ambient air quality standards (*see* Table 27). However, no country has a separate emission limit for $PM_{2.5}$ from coal-fired power plants. $PM_{2.5}$ from coal combustion is still regulated as part of particulate matter.

Different countries base their standards on different time periods, ranging from hourly average to annual averages. Germany also has half hourly average emission limit values. This affects the actual emission levels resulting from a standard. For example, if a power plant had to stay below a certain limit for every hour of the year, the operator would have to leave the room for hour-to-hour variations, resulting in a much lower annual average than if the same limit had to be met on a yearly average basis. In fact, although the time average period for ambient air quality standard is specified in detail, many countries do not clearly specify the time average period for their emission standards for coal-fired power plants.

Table 27 International and national air quality standards

Country	NOx, µg/m³		SOx, µg/m³		$PM_{2.5}$, µg/m³	
	24 hrs	annual	1 hr	24 hrs	24 hrs	annual
WHO	200	40	200	20	25	10
EU	200	40	350	125		25
Australia	246	62	572	220	25	10
China	250	50	500	150	75	35
India		40		80	60	
Indonesia	400	100	900	365	230	90
Japan			286	114	35	15
South Africa	200	40	350	125	40	20
Thailand	320	57	780	300	50	25
USA	205	109	214		35	

The reference conditions vary from country to country. Most countries use 0°C and 101.3 kPa in dry flue gas as the reference condition. But Indonesia and Thailand carry out their tests at 25°C. For NOx measurement, the EU, China and South Africa, allow 6% O_2 in dry flue gas while Australia, Indonesia and Thailand allow 7% O_2. Australia measures SOx as SO_3, while other countries as SO_2. Japan regulates sulphur oxide emissions on the basis of a value estimated from a constant K, which varies according to the designated area and the effective stack height.

Different countries also use different units. The USA set limits based emissions per unit of electricity produced, while Japan and Thailand use parts per million in flue gas. The EU, Australia, China, Germany, India, Indonesia and South Africa regulate pollutant concentration per cubic metre of flue gas.

Generally speaking, new plants have tougher ELVs. However, the definitions for new and existing power plants are different from country to country. But most of the countries regulate pollutant emissions based on the plant's age. America has the most complicated age (eight) variations in their emission standard.

All these differences make the comparison of different countries' emission standards almost impossible. Based on the discussion in this chapter (*see* Table 28), currently, China has the toughest rules for coal-fired power plants, although its air quality standards are less strict than those for the WHO and EU.

The emission standards for each country and region changes frequently. Each time it changes, it becomes stricter. The binding emission limits should be based on what the BATs can achieve, and relate to associated emission levels of BAT. The authorities set the emission limit values on the bases of BAT-AELs. ELVs that exceed BAT-AELs, as they are unlikely to be met.

Table 28 Selected countries' emission standards for NOx, SOx and PM from coal-fired power plants

Country	Time period	NOx, µg/m³		SOx, µg/m³		PM, µg/m³	
		existing	new	existing	new	existing	new
Australia			800		200		80
China	hourly	100	50	200/50	35	30/20	10
Germany	daily	200	150	200	150	20	10
India		600/300	100	600/200	100	100/50	30
Indonesia		850	750	750	750	150	100
Japan[1]		410	200		200	100	50
South Africa	continuously	1100	750	3500	500	100	50
Thailand		820	410	2002	515	180	80
USA[1]	daily	135	95.3	185	136	18.5	12.3
EU IED	continuously	200	150	200	150	20	10

[1] Conversion Zhu and Wang (2014)

The cost of implementing the new standards is high. The EU's draft LCP BREF proposed tougher emission limit values which led to some counties complaining about the severe economic impact of their implementation. China has to face the similar economic constraints in implementing the new emission limit for coal-fired power plant.

3 Standard methods for sampling and measurement

Emissions legislation can only be complied with if sources of pollution are identified and appropriate control measures taken. Without standard sampling and measurement methods, data from different studies are not directly comparable. However, sampling and measuring of particulate matter, especially $PM_{2.5}$, at any source is not easy. Because of the presence of volatile and semi-volatile species, there is no definitive description of what does and does not comprise $PM_{2.5}$. It is assumed that all material caught in a designated $PM_{2.5}$ sampler will be $PM_{2.5}$ and will not react with other captured species or re-volatilise between sampling and final analysis. Sampling conditions must be controlled to avoid the formation of artefacts because some of the sample may be reaction products and/or temperature or moisture sensitive species. It is important that the results of any particulate measurement study make it clear which sampling method was used and which species (particulate and/or condensable species, primary or secondary particulates) are included in the measurement. Sloss (1998, 2004) carried out comprehensive reviews on sampling and measuring methods for PM_{10} and $PM_{2.5}$ emissions from coal-fired power plants and PM_{10} and $PM_{2.5}$ in ambient air. This chapter briefly summaries her findings and updates on developments since 2004. As secondary $PM_{2.5}$ sources, NOx and SO_2 are relatively simple to measure and the methods are well established. Over the years, IEA CCC has carried out a number of studies on various aspects of NOx and SOx emission control at coal-fired power plants, including sampling, measuring and testing methods (visit www.iea-coal.org for details). This report concentrates on primary $PM_{2.5}$ and total $PM_{2.5}$ sampling and measuring methods, and on condensable $PM_{2.5}$.

The sampling and measurement of fine particulates at sources such as coal-fired power plants is problematic for several reasons:

- particulates measured in ambient air downstream of a source are actually a combination of primary particles and secondary particles formed from precursors in the stack, as well as from reactions with other pollutants in the ambient air. Particulates in the stack gases are cooling and therefore also represent a combination of primary and secondary particles, but not necessarily those that would form when the plume mixes with polluted air;
- the primary particles are small and tend to bounce in standard particulate capture systems;
- the particles are present in very low concentrations. Testing for compliance is even more challenging now with the lower emission limits;
- precursor species and other emitted gases can form secondary products in the measurement systems which may, or may not, represent those which would genuinely have formed in the ambient air (Sloss, 2004).

In order to compare results from different studies, it is necessary to have a standard $PM_{2.5}$ sampling and testing technique. Since Sloss's review in 2004, three ISO standards have been issued and adopted by some countries. The US EPA has updated their method 201 and 201A. After a brief introduction of the technical terms for sampling and measuring equipment and systems, this chapter summarises the three new international standards. Some countries' national sampling method standards, such as the US EPA's methods, are also covered.

3.1 The basics of sampling and measuring

$PM_{2.5}$ measurement can be divided into two distinct types, those which:

- collect the sample in a form which may be weighed and, sometimes, subjected to chemical analysis;
- measure the particles directly, but do not collect any sample, or at least do not collect the sample in a form which may be weighed and/or otherwise analysed.

An efficient $PM_{2.5}$ sampling system should include a 2.5 μm size selective inlet, nitric acid removal denuders, filter holders or collection substrates, flow controllers and pumps. Cyclones and impactors are commonly used as 2.5 μm size cut-off inlets to separate fine particles from larger ones.

Cyclones (*see* Figure 2) use centrifugal force in a conical shaped chamber to remove larger particles from the swirling gas stream. The incoming gas stream is forced into a circular motion as it passes down the cyclone. At the bottom of the cyclone, the gas spirals up through the centre tube and out at the top. Particles in the gas stream are forced to the wall by the centrifugal force, but retarded by the drag of the gas stream. The larger particles impact the inside surface of the cyclone, whilst smaller particles travel through to the downstream collection system. Cascade and sharp-cut cyclones are often used to select $PM_{2.5}$.

An **impactor** is any device which is used as a deposition site for particles. It consists of a series of nozzles and impaction plates, which separate particles according to their aerodynamic diameter. The sample stack gas is drawn through a nozzle onto a plate at a previously determined volumetric flow rate. The plate causes the gas to be deflected at 90 degrees along its surface. The selective deposition of particles onto impactors is based on sampling effectiveness curves. Larger particles have longer stopping distances than smaller ones. Inert objects, such as particles, cannot effect a change of direction of 90 degrees in a distance less than their stopping distance. A curve or bend can therefore be used to select larger particles by collecting them in the 'corner', whilst smaller particles complete the turn and continue to the sampling device (*see* Figure 3). Each impactor plate has a cut-off point where the rest of the particles of a certain aerodynamic diameter, for example 2.5 μm, are deposited on the plate and 50% pass through to the next stage. Types of impactors include slot-type, round nozzle, and virtual (ISO, 2009; Sloss, 2004).

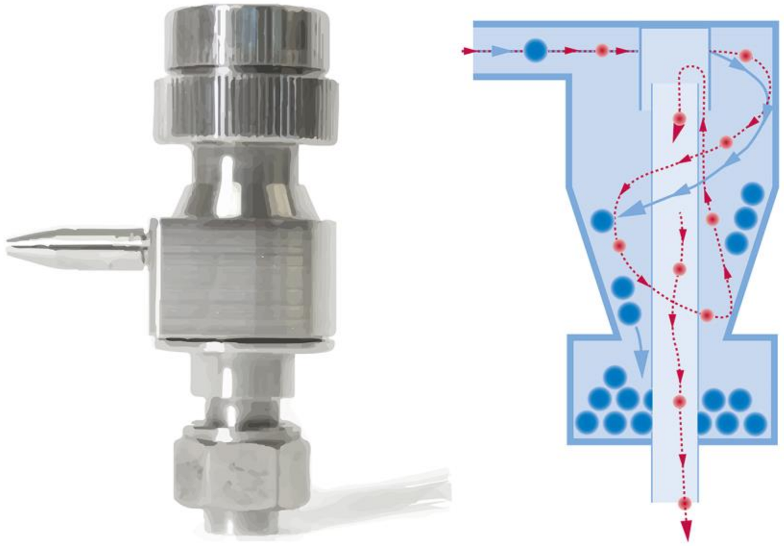

Figure 2 A $PM_{2.5}$ cyclone and how it works

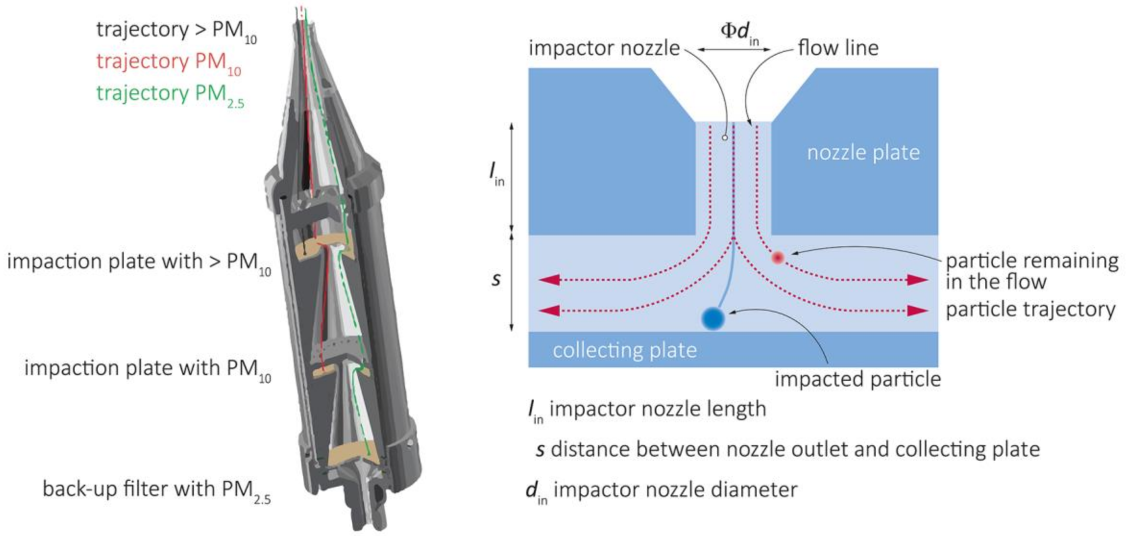

Figure 3 An impactor and how it works

The equipment commonly used to sample/collect $PM_{2.5}$ includes filters, impactors, cyclones, and tapered element oscillating microbalance (TEOM). One of the most common collection methods is a **filter**. A selection of filter materials is available, for example glass fibre, quartz, polymer, nylon, Teflon and Nucleopore. The selection depends on what species are to be targeted and which analysis method will be used. Apart from their use as size selection inlets, **impactors** can also be used to classify particles into sub-groups by size. For example, the ISO 23210:2009 standard method (*see* Section 3.2.1) uses two-stage cascade impactors to divide particles into three factions. **Cyclones** are used as collection systems as well, for example in ISO 25597:2013 (*see* Section 3.2.1). **TEOM** is based on an oscillating filter attached to the tip of a hollow, tapered, oscillating glass rod. The change in oscillating frequency is used to measure directly the accumulation of mass on the filter over time. By relating the increasing weight to the gas flow rate, a value for the particulate matter concentration can be determined every two seconds. TEOMs have been used extensively for ambient monitoring of fine particulates. In-stack TEOM systems are also available.

Sampling and measuring within stacks are particularly difficult due to the elevated temperatures (>260°C) and high moisture conditions. $PM_{2.5}$ contains both volatile and semi-volatile materials. At a temperature up to 260°C, many organic species are in gaseous form, but could condense onto particles or form secondary species as the flue gas disperses and cools. Problems can arise with many $PM_{2.5}$ sampling systems when the stack gases are moist or wet with entrained or condensed water. Water may be attached to the particles and change the flow characteristics in addition to adding weight to the sample being measured. These problems can be dealt with in one of three ways:

- a dilution sampling system can be used to avoid the condensation of water;
- the sample may be cooled and conditioned to allow conventional equipment to be used; or
- the system can be operated at a suitable elevated temperature to avoid moisture condensation.

$PM_{2.5}$ must be measured by different techniques since it exists in different forms. For example, filtration or impaction methods are for primary particles and condensation methods are for the secondary particles. Sloss (2004) classified measuring methods as:

- primary particles methods – manual and automated;
- condensable/secondary particles method – dilution systems; and
- total measurement systems – sampling trains and dilution sampling trains.

Sloss's definition of 'primary particles' here is similar to the US EPA's '**filterable particulate matter**' which means particles are emitted directly by a source as a solid or liquid at stack or release conditions, and are captured on the filter of a stack test train. **Condensable particulate matter** (CPM) is emitted to a stack in vapour form, but condenses upon cooling and dilution in the ambient air to form a solid or liquid particulate immediately after discharge from the stack. Condensable particulates are generally smaller than 2.5 µm. Furthermore, condensable particulates may react with air stream components as they condense. In fact, the ISO method defines CPM as particulate matter formed at temperature below 30°C due to physical and/or chemical processes. **Total particulate matter**, also known as **primary particulate matter**, are the particles entering the atmosphere as a direct emission from a stack or an open source. It has two components: filterable particulate matter and condensable particulate matter.

Manual methods used to measure filterable $PM_{2.5}$ include gravimetric (weighing) systems which collect the particles on filters, cyclones and impactors for subsequent weighing and/or chemical analysis. Most gravimetric sampling systems involve a nozzle and probe which is inserted into the stack. The sample is withdrawn isokinetically through the sample probe and into the particle collection device (such as a filter, cyclone or impactor). The collection device can be located inside the stack or outside. If the system is outside, then it must be heated to stack temperature to prevent condensation. In order to ensure that a representative sample is obtained, samples must be taken isokinetically from several locations across the stack and the total averaged.

Automated systems are usually used for particulate monitoring and do not collect a sample for analysis. They include TEOM, beta attenuation, and optical techniques.

Sampling trains to measure total particulates are formed by placing a filterable particle sampling system, such as a filter or impactor, to collect the filterable PM followed by an impinger to capture the condensable particles.

The **dilution sampling train** uses in-stack sampling cyclones to measure filterable particles in the same manner as the basic sampling train, but in addition, utilises extra $PM_{2.5}$ and/or PM_{10} cyclones in the sampling train to measure particles formed in the dilution chamber. To determine both filterable and condensable PM_{10} and $PM_{2.5}$, the sample gas is rapidly mixed and cooled with non-reactive gases such as nitrogen and oxygen or dilution air. The dilution system simulates the dilution and cooling processes that occur in the near field of a stack plume as it mixes with the atmosphere. These processes impact the homogeneous and heterogeneous nucleation of stack gas constituents. The diluted sample can then be analysed for particulate matter or gases, depending upon the requirements of the test. More details about the dilution sampling train are described in Section 3.2 (US EPA Method 202 and ISO 25597:2013).

Since the dilution sampling system was selected by the US EPA to measure condensable PM and total PM, various types of dilution systems for the measurement of $PM_{2.5}$ have been developed. The compact sampler designed by Li and others (2011) enhances mixing of dilution air with the stack gas, and thus shortens the length of the mixing section. It decreases the nominal flow rate through the aging section and reduces the size of the residence chamber accordingly. Sampling gas enters the residence chamber under pressure, and air pressure in the chamber is micro-positive. Uncollected redundant gas is automatically discharged through unused sampling ports, which keeps the unit stable. Kong and others (2013) designed a dilution sampling system to study the emission and profile characteristic of polycyclic aromatic hydrocarbons (PAHs) in particles, especially for PM_{10} and $PM_{2.5}$ emitted from stationary sources. Natural Resources Canada (Win Lee, 2013) has produced four dilution based prototype systems for measurement and characterisation of fine PM emissions from stationary combustion sources. The third generation sampler, known as CETC-3, uses a regular stack sampling probe, and particulate size segregation is done using sampling cyclones with different cut sizes installed external to the ageing chamber. CETC-3 measures the dilution ratio using a CO_2 tracer gas technique, moisture injection to provide variable sample humidity, and longer residence time. The latest prototype CETC-4 has an optional in-stack $PM_{2.5}$ cyclone on the probe. The CETC-4 sampler is simpler to operate, and more compact than CETC-3 as it has no humidification system. It also has an interchangeable mixing section that allows variable residence times.

Finland Dekati Ltd designed an Electrical Low Pressure Impactor (ELPI) to test aerosol particle size distribution, concentration and size-classified particle charge distribution measurements in a coal-fired power plant (Niemelä and others, 2008). The ELPI is coupled with a sampling and dilution system, called FPS, to form a complete measurement system for fine particle emissions measurements from power plants. The dilution system allows sampling from hot flue gas and provides a controlled temperature decrease with minimal losses. Its operation is based on an ejector pump where compressed dilution air is used to create sample suction in a conical nozzle. Dilution air flow is kept constant using critical flow control orifices. Sample flow is dependent on the pressure drop across the ejector, which is measured by two pressure sensors. Results from ELPI measurements are comparable to those from gravimetric techniques.

3.2 International and national standards

This section describes various international and national measuring standards.

3.2.1 International standards

Standards are developed internationally by ISO and by the Comité European de Normalization (CEN). A standard developed by ISO is prefixed 'ISO' and by CEN is prefixed with 'EN'. ISO standards are accepted on a case-by-case principle; it is not mandatory for a member country in the European Union to adopt an ISO standard. However, CEN standards must be implemented by member countries.

During the last few years, ISO has standardised three measurement methods which use impactors, virtual impactors or cyclones to determine the mass concentration of PM_{10} and $PM_{2.5}$ in flue gas in the stack. One of these has also been adopted by CEN.

EN ISO 23210:2009 Stationary source emissions – determination of PM_{10}/$PM_{2.5}$ mass concentration in flue gas – measurement at low concentrations by use of impactors

A standard reference method for the determination of PM_{10} and $PM_{2,5}$ mass concentrations at stationary emission sources using two-stage cascade impactors is specified. During sampling, the particles are divided into three factions:

- first impactor: particles with aerodynamic diameters greater than 10 µm;
- second impactor: particles with aerodynamic diameters between 10 µm and 2.5 µm; and
- backup filter: particles with aerodynamic diameters smaller than 2.5 µm.

First, greased collecting plates are used to increase the adhesion and to reduce possible rebound of particles to evaluate the optimum separation efficiency under laboratory conditions. Second, quartz-fibre filters (with the smooth surface towards the top) are used as collecting plates, as in the intended operation of the impactor. Tests with at least six different particle diameters between 1 µm and 10 µm are required at the $PM_{2.5}$ stage. The separation curves of PM_{10} and $PM_{2.5}$ emission measurements correspond to the separation curves for PM_{10} and $PM_{2.5}$ ambient air quality measurements specified in ISO 7708:1995 (*see* Figure 4).

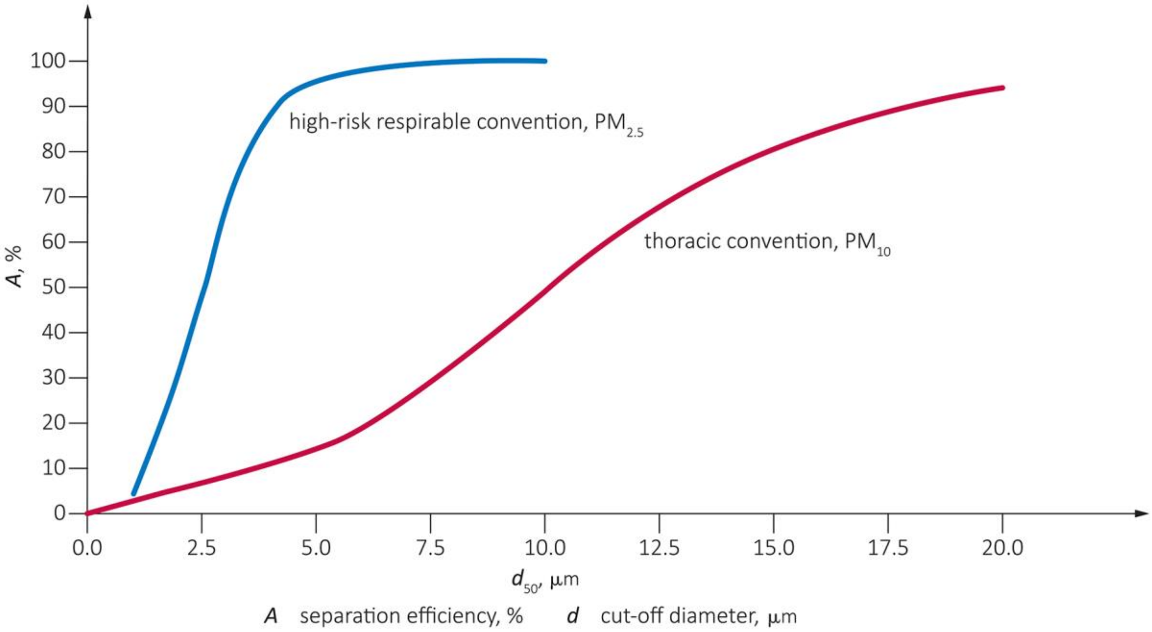

Figure 4 Separation curves of PM_{10} and $PM_{2.5}$ specified in ISO 7708:1995 (BS EN ISO, 2009)

Figure 5 shows an example design of the sampling system. A straight entry nozzle is recommended for in-stack measurement. In-stack measurements with a goose-neck nozzle in front of the impactor can cause higher particle losses in the probe. Furthermore, out-stack measurements require an exact external thermal control of the impactor to meet the exact cut-off diameter. In-stack measurements with a goose-neck nozzle in front of the impactor require extensive validation experiments to be performed, including the quantification of losses related to coarse and fine particles. These measurement setups are only used if losses of particles in the sampling train are below 10% of the total mass of fine particles collected on the collecting plate and backup filter. ISO 23210:2009 standard describes the design, use and theory of round-nozzle impactors. It does not exclude other types of impactors, provided these systems meet the performance criteria specified in the standard in a validation of the impactor performed by an independent testing laboratory.

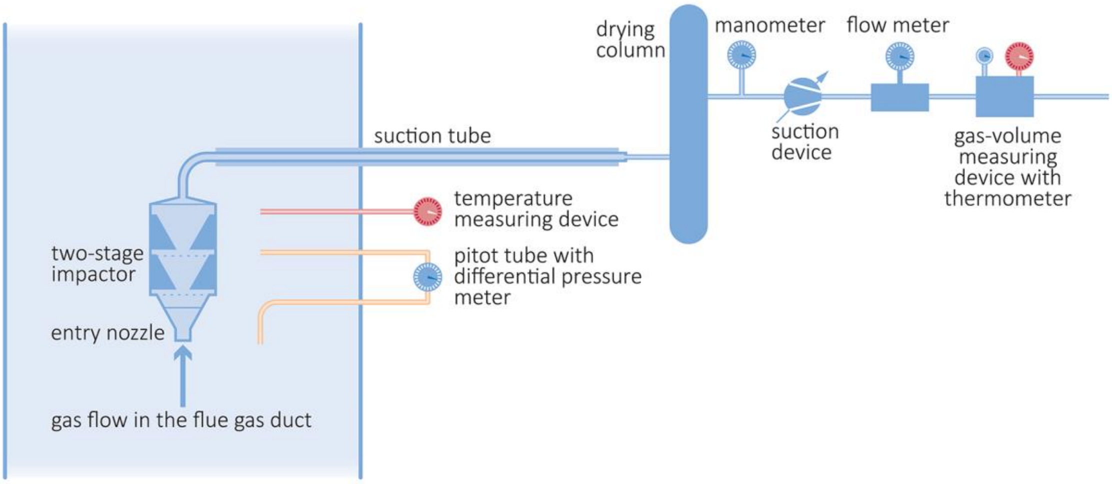

Figure 5 Design of $PM_{2.5}$ in-stack sampling system by use of impactor (BS EN ISO, 2009)

The preparation, measurement procedure and post-treatment are also described in the ISO 23210:2009 standard. In general, the dimensions of the measurement ports should allow straight insertion of the impactor into the flue gas duct without any contact with the inner duct walls. The flue gas conditions should be constant during sampling to ensure that the isokinetic rate is kept between 90% and 130% of the calculated value. The sampling point must be representative of the flue gas velocity, and the cut-off diameter should not change during sampling. A blank sample is taken as a quality control measure after each measurement series, or at least once a day. The calculation method, performance characteristics, and reporting method are also included in the standard.

This measurement method is especially suitable for the determination of mass concentrations below 40 mg/m^3 as half-hourly averages under standard conditions (0°C, 101.3 kPa, dry gas). It is not applicable to the sampling of flue gases that are saturated with water vapour. The stack gas dew point must also be below the stack gas temperature.

ISO 13271:2012 Stationary source emissions – determination of PM$_{10}$/PM$_{2.5}$ mass concentration in flue gas – measurement at higher concentrations by use of virtual impactors

This method is based on the principle of gas stream separation using two-stage virtual impactors without impaction plates. It is especially suitable for in-stack measurement of particle mass concentrations in flue gas, including those with higher dust concentration than *ISO 23210:2009*. It can also be used for flue gas which contains highly reactive compounds (sulphur, chlorine, and nitric acid) at a high temperature or in the presence of high humidity.

The first stage of the two-stage virtual impactor separates the largest particles using a particle collection nozzle. The coarse particles are collected on a plane filter. Smaller particles are then divided into the same three fractions as ISO 23210:2009 by the two-stage virtual impactor for sampling. PM$_{2.5}$ particles are collected on a backup filter (*see* Section EN ISO 23210:2009). The separation curves are as specified in ISO 7708:1995 (*see* Figure 4). Figure 6 shows the design of the sampling system for this method. Nozzle specification and test requirements are similar to ISO 23210:2009, as described previously. The impactor must be operated with a constant sample volume flow rate, which depends on the flue gas conditions. Equipment and working materials are specified in the standard. For example, the virtual impactor must be made of corrosion proof material, such as titanium or stainless steel. Preparation, measurement procedure and post-treatment requirements are also given.

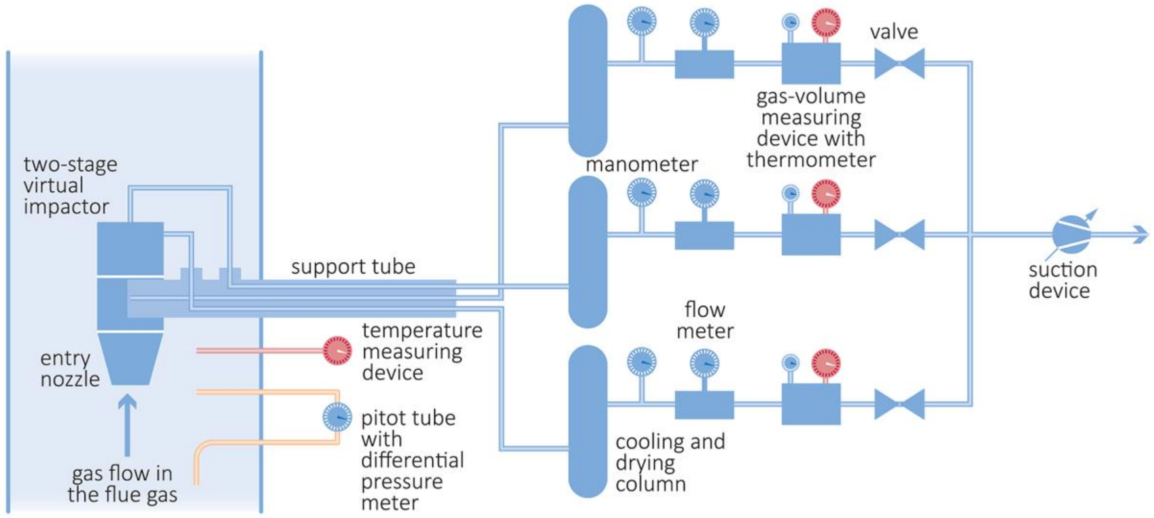

Figure 6 Design of virtual impactor sampling train (BS ISO, 2012)

ISO 25597:2013 Stationary source emissions – test method determining $PM_{2.5}$ and PM_{10} mass in stack gases using cyclone samplers and sample dilution

Standard ISO 25597 was published in 2013 (BS ISO, 2015). It specifies procedures for the extraction and measurement of flue gas from stationary sources:

- filterable particulate matter by the use of basic cyclone samplers; and
- filterable and condensed particulate matter by the use of dilution samplers.

The basic sampling train (*see* Figure 7) measures filterable particles using sampling cyclones that can distinguish between particle sizes in the range of 2.5 µm and 10 µm. The first cyclone separates the PM_{10} particles and the second one separates $PM_{2.5}$. Sampling is conducted isokinetically at sampling points on the sampling cross-section determined according to ISO 9096. This method is especially suitable for measurements of particle mass concentrations above 50 mg/m³ as a half-hourly average at standard conditions (293 K, 101.3 kPa, dry gas).

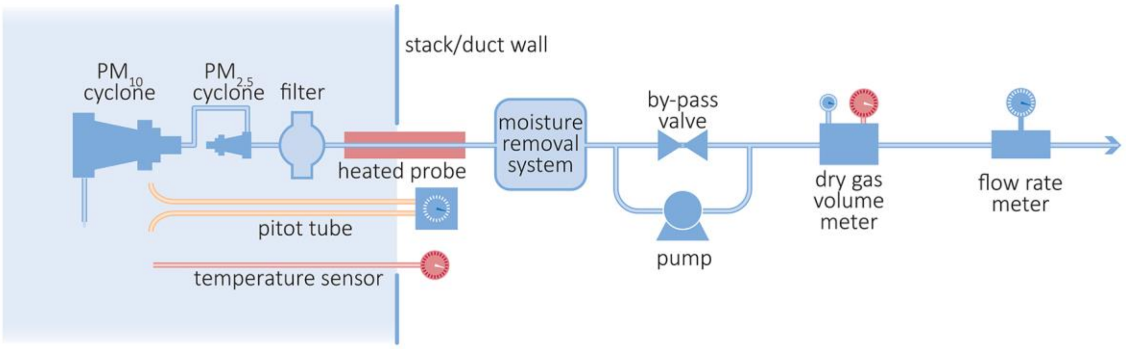

Figure 7 In-stack combined PM_{10} and $PM_{2.5}$ cyclone basic sampling train (BS ISO, 2015)

The dilution sampling train (*see* Figure 8), as described in Section 3.1, uses in-stack sampling cyclones to measure filterable particles in the same manner as the basic sampling train, but in addition, utilises extra $PM_{2.5}$ and/or PM_{10} cyclones to measure particles formed in the dilution chamber. PM_{10} and/or $PM_{2.5}$ cyclones are attached to the probe. The sample then passes into the mixing section of the dilution chamber where it is mixed and cooled with humidified air at a ratio of at least 20:1. After dilution, the aerosols are aged in the aging zone for a minimum residence time of 10 seconds. The aged gas is then pulled through a secondary $PM_{2.5}$ cyclone, a single stage PTFE membrane filter or equivalent, and the particulate and condensable matter are collected for subsequent gravimetric measurement.

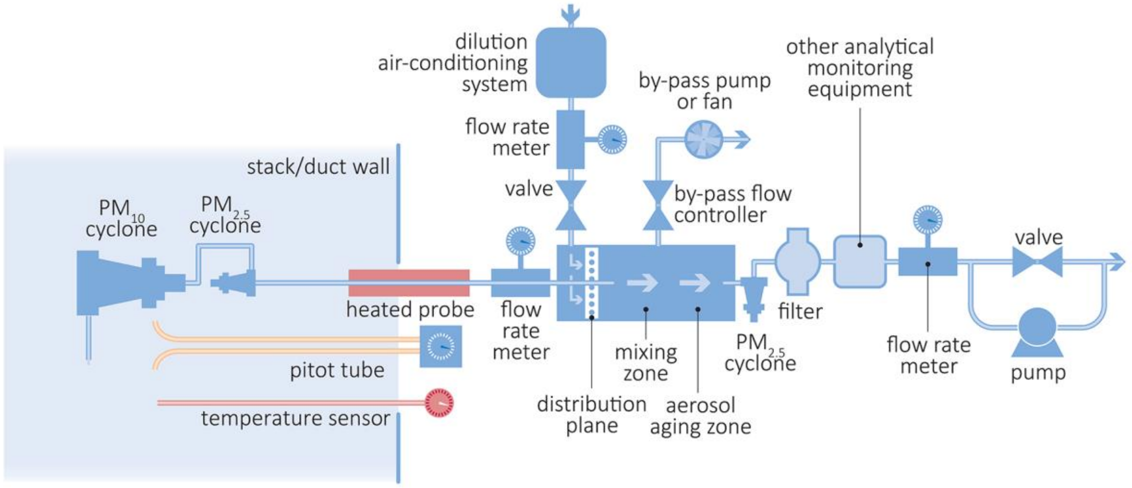

Figure 8 In-stack combined PM_{10} and $PM_{2.5}$ cyclones with dilution sampling train (BS ISO, 2015)

The dilution sampling train can be used in combination with the basic sampling train. The dilution sampling system is intended for applications where measurement is required of particles similar in characteristics to materials formed when a flue gas exhaust mixes with ambient air. Particulate matter filter samples collected using dilution sampling can be further analysed to provide chemical composition.

Near-isokinetic sampling within 80% to 120% of the isokinetic sampling rate is allowed for $PM_{2.5}$ sampling. This method has been applied to emission sources with a low moisture content and to saturated moisture stack gases. However, the method is not applicable to effluents where entrained water droplets are present.

There are some combustion processes and situations that can limit the applicability of this standard. Where such conditions exist, caution and competent technical judgment are required, especially when dealing with any of the following:

- high vacuum, high pressure or high temperature gas streams above 260 °C;
- fluctuations in velocity, temperature or concentration due to uncontrollable variation in the process; and
- gas stratification due to the non-mixing of gas streams.

There are also limitations specific to each sampling technique. Stacks with entrained moisture droplets can have droplet sizes larger than the cyclone cut sizes for the cyclones. These water droplets normally contain particles and dissolved solids that become PM_{10} and $PM_{2.5}$ following evaporation of the water. For dilution sampling, this method concerns the presence of particles in the dilution air at very low concentrations, contributing to measurement background. This can be significant for certain very clean sources. Dilution air system blanks are necessary when sampling sources with anticipated $PM_{2,5}$ or PM_{10} mass concentrations of less than or equal to about 1.0 mg/m^3.

Ways of avoiding measurement bias are described. For example, maintaining the sample probe at a temperature at or slightly above the stack gas temperature may minimise thermophoretic losses. Also, sharp changes in flow direction should be avoided to minimise inertial losses. Finally, the humidity of the diluted sample should be kept below 70% to maintain particle growth conditions.

3.2.2 USA

The USA was the first country to standardise the sampling and measuring methods for fine PM emissions. Therefore, its methods are reviewed before other countries in this report. The EPA issued two standard reference methods for measuring $PM_{2.5}$, namely Method 201A for Filterable $PM_{2.5}$ and Method 202 for condensable PM. Combining the two methods could obtain total $PM_{2.5}$ emissions. The historic sampling method, CTM – 039, which is still being used is also described.

Method 201A – Determination of PM_{10} and $PM_{2.5}$ emissions from stationary sources (constant sampling rate procedure)

Method 201A was first developed prior to 1990 for PM_{10} sampling. The old method was reviewed by Sloss in 2004. The EPA revised Method 201A in December 2010 by adding a $PM_{2.5}$ cyclone to measure both PM_{10} and $PM_{2.5}$ emissions (*see* Figure 9). The revised Method 201A categorises three classes of particles:

- diameter larger than10 μm;
- diameter equal to or smaller than 10 μm but larger than 2.5 μm; and
- PM diameter equal to or smaller than 2.5 μm.

With the exclusion of the PM_{10} cyclone, the sampling train can be used to measure total and $PM_{2.5}$ emissions. 80% to 120% of isokinetic flow is needed to obtain PM_{10} and $PM_{2.5}$, and 90% to 110% for total filterable particulate. Well-defined limits must be established to minimise variations in the isokinetic sampling conditions. In-stack filterable particulate samples are taken from a recommended maximum of 12 sampling points, at a constant flow rate through the sampling train, and with a filter at the stack temperature.

This method has some limitations. First, it is not applicable to wet sources. The EPA recommends that for those sources the total filterable PM is reported as filterable $PM_{2.5}$. Second, train blank correction is not permitted (although the EPA reported that the blank was 0.9 mg). Consequently, results have a positive bias.

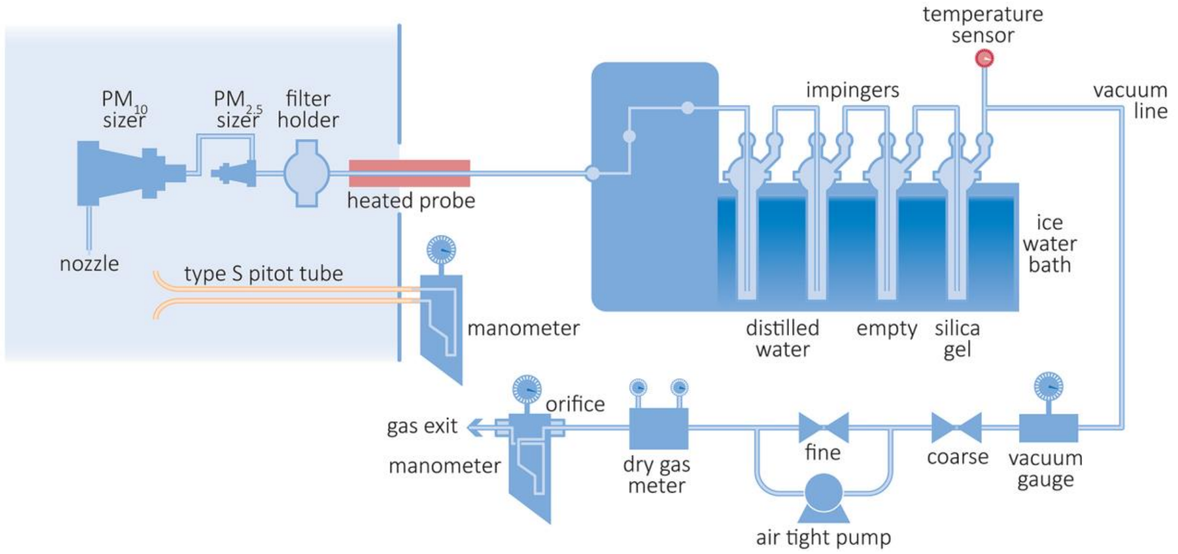

Figure 9 Schematic of US Method 201A sampling train (EPA, 2010a)

Method 202 – Dry impinger method for determining condensable particulate emissions from stationary sources

This standard method addresses the equipment, preparation and analysis necessary to measure only condensable particulate matter (CPM). CPM is measured after removal from the stack and after passing through a filter.

Method 202 was first promulgated in December 1991 and reviewed by Sloss in 2004. It was reported that the results had a significant positive bias and lacked the requisite reproducibility. The primary source of the bias was sulphur dioxide, which is collected in the sampling train impinger water. There it reacts with the water to forms sulphate, which is detected as $PM_{2.5}$.

The EPA published the revised method in December 2010. It eliminates the use of water as the collection medium in impingers and includes the addition of a condenser followed by a water dropout impinger immediately after the final in-stack or heated filter. It also includes the addition of one modified Greenburg Smith impinger (back-up impinger) and a CPM filter after the water dropout impinger. CPM is collected in the water dropout impinger, the modified Greenburg Smith impinger, and the CPM filter. Using dry impingers is intended to eliminate any sulphate artefacts. Figure 10 presents a schematic of the sampling train configured with these changes.

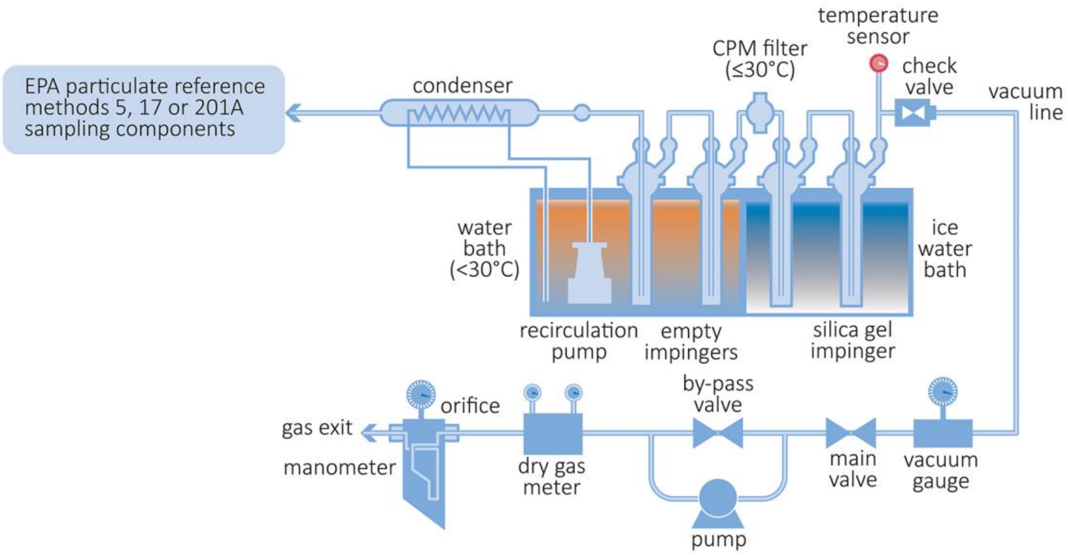

Figure 10 Schematic of US Method 202 CPM sampling train (US EPA, 2010a)

The impinger contents are purged with nitrogen immediately after sample collection to remove dissolved SO_2 gases from the impinger. The CPM filter is extracted with water and hexane. The impinger solution is then extracted with hexane. The organic and aqueous fractions are dried and the residues are weighed. The total of the aqueous and organic fractions represents the CPM.

The potential artefacts from SO_2 are reduced using a condenser and water dropout impinger to separate CPM from reactive gases. No water is added to the impingers prior to the start of sampling. To improve the collection efficiency of CPM, an additional filter ('CPM filter') is placed between the second and third impinger. The isokinetic sampling conditions of the filterable PM test method must be met.

The new Method 202 is an improvement on the old method, especially for low-concentration sources, but it is more expensive.

Yang and others (2014) used the two methods 201A and 202 to measure and characterise $PM_{2.5}$ emissions from 5 different stationary sources. One of these was a coal-fired power plant. The results showed that it is necessary to collect both filter and cyclone holder residue particulates to avoid underestimation of $PM_{2.5}$ emissions, especially for stacks with low $PM_{2.5}$ concentrations. The stack temperature was the most important factor affecting the percentage of condensable PM. The SO_2 and other condensable materials are easier to condense on the filter at the cooler temperatures, resulting in higher percentages of filterable PM. This again indicates the importance of including condensable PM in the measurement of $PM_{2.5}$ emissions since stack temperature can affect filterable PM measurements in Method 201A.

CTM-039 Measurement of $PM_{2.5}$ and PM_{10} emissions by dilution sampling (constant sampling rate procedures)

In 2004, long before the EPA revised Method 201A, they added a $PM_{2.5}$ cyclone between the PM_{10} cyclone and in-stack filter of Method 201A, and added and modified various Method 201A procedures. Initially, the new method was called Preliminary Method PRE 4, and then changed to CTM-040 (conditional test method). CTM-039 expanded and replaced method CTM-040 by:

- incorporating a $PM_{2.5}$ sizer cyclone behind (or replacing) the PM_{10} sizer cyclone as in CTM-040;
- removing the in-stack filter;
- diluting the sample gas utilising a mixing cone and residence chamber;
- using a dilution air system to supply clean air at a temperature less than 30°C (low enough to achieve a filtration temperature of less than 30°C) and a relative humidity less than 50%;
- adding a 142 mm filter to the residence chamber exit to capture any particulate that passes through the residence chamber; and
- providing a sample stream and extraction location for speciating $PM_{2.5}$ in a manner similar to that used for ambient $PM_{2.5}$ speciation.

The results from CTM-39 are encouraging but the equipment is expensive. CTM-039 belongs to EPA's 'Historic Conditional Methods' category. This category is closed and no new methods will be added to it. However, the procedure is still being used.

3.2.3 Canada

Canada has three reference methods for measuring $PM_{2.5}$ emissions from stationary sources. They may be used separately or jointly to determine filterable and condensable particulate matter, which are considered as primary $PM_{2.5}$ (Environment Canada, 2013).

Method G: Determination of filterable $PM_{2.5}$ and filterable particulate matter

Method G is similar to US Method 201A. PM samples are withdrawn at a near-constant rate, but isokinetically, from pre-determined traverse points. The filterable $PM_{2.5}$ is separated with an in-stack cyclone, and deposited in the probe and on an out-of-stack heated filter maintained at a temperature of 120 ± 14°C or at such other temperature as is necessary to prevent blinding of the filter by condensation. The filterable $PM_{2.5}$ and filterable PM are determined gravimetrically after removal of un-combined water. Three valid tests are required for their determination. Each test must last a minimum of two hours and collect at least 1.5 m^3 of stack gas on a dry basis at reference conditions. Stack gas temperatures must be lower than 260°C to avoid damage to the $PM_{2.5}$ cyclone.

Method H: Determination of condensable particulate matter (CPM)

This method is similar to US EPA Method 202. PM is isokinetically withdrawn from the stack and filtered at a temperature of 120 ±14°C. The filtered gas sample is then cooled in an ice-water jacketed coil condenser and any moisture that may condense is collected in a condensate trap or stemless impinger. Ethanol is added to the impinger to inhibit the oxidation of SO_2 that may be dissolved in the condensate. Any aerosol formed during the cooling is collected by a secondary or mist filter held at ambient temperature. At the completion of the test, the sample is recovered quantitatively and the condensate is extracted with dichloromethane. The organic fraction is evaporated at ambient temperature, whereas the aqueous fraction is evaporated to near-dryness in a 105°C oven. Drying is completed in a desiccator and the residue weighed.

Three valid tests are required for the determination of condensable particulate matter. Each test must run for a minimum of two hours and collect at least 1.7 m^3 of stack gas on a dry basis at reference conditions. This method has not been evaluated for sampling times over four hours and condensate catches beyond 250 g.

Method I: Options

This method is used to measure the mass concentration and mass emission of filterable $PM_{2.5}$ and CPM released from stationary sources. The front-half of Method G is combined with the back-half of Method H to form a method for sampling total $PM_{2.5}$ from stationary sources. The method is subject to the limitations of Methods G and H.

3.2.4 Other countries

Many countries have not set up their own standard methods for sampling and measuring. Most of the EU member countries have adopted ISO or EU standards. Other countries follow either the US EPA's or ISO's standard methods or both. For example, the **UK** Environment Agency issued a *Technical Guidance Note M15* for monitoring PM_{10} and $PM_{2.5}$ emissions from stacks (UK EA, 2012) and *Technical Guidance Note M2 f*or monitoring stack emissions (UK EA, 2013). The UK has adopted all three ISO standards but only mentioned EN ISO 23210 in Technical Guidance Note 15 to monitor $PM_{2.5}$. EN ISO 23210 and ISO 25597 are recommended in Technical Guidance Note M2 for particulate matter testing. '*The determination of particulates and sampling methods of gaseous pollutants from exhaust gas of stationary source (GB/T 16157-1996)'* is the official standard method in China. However, the previously mentioned ISO and US EPA methods have commonly been used in recent years (Shi and others, 2015; Wang and others, 2013).

3.3 Comments

Sampling and analysis of source emissions is crucial for compliance monitoring, and for source appropriation and epidemiological studies. ISO has developed three standard methods, whilst the USA and Canada have their own standardised methods. However, the measurement of $PM_{2.5}$ still remains a challenge. Further work is required to determine the best approach to measure fine particulates accurately so that all research groups can use the same approach to produce comparable and reliable data.

The majority of fine particulate sampling and measuring methods still concentrate on total mass or particle distribution. High quality and comprehensive measurements of the chemical components of $PM_{2.5}$ are still an important goal for the future. A full analysis of the complete chemistry of fine particulates requires the measurement of almost every known atmospheric pollutant. The measurement of the chemical components of $PM_{2.5}$ needs to be reviewed and the evidence requirements clearly stated.

Errors can be introduced easily. For example, between sampling and final weighing, the filter is exposed to various ambient conditions of temperature and humidity which could lead to additional variation in the measured concentration of semi-volatile and hygroscopic materials. Storage and treatments, such as equilibration, also lead to loss of some chemical species. As the sample sizes collected from PM_{10} and $PM_{2.5}$ studies are so small, weighing and handling of filters can also be a major source of error.

4 Control technologies

As discussed in the previous chapters, $PM_{2.5}$ is made up of two fractions – primary and secondary particles. The formation and behaviour of these two fractions are so distinct that their control tends to be dealt with separately. Part of primary $PM_{2.5}$, also known as filterable particulate matter in the measurement standards, can be controlled as fine particulate matter. Secondary $PM_{2.5}$ which is mainly formed from SO_2 and NOx, can be controlled as acid gases. Technologies are now available that efficiently remove two or more pollutants simultaneously in a single system. Pollution control technologies at coal-fired power plants have been extensively reviewed by IEA CCC. Selected reports are listed below. Information about the reports can be found at: www.iea-coal.org/site/2010/publications-section/reports.

PM control

- Nicol (2013) Recent developments in particulate control, CCC/218
- Zhu (2003) Developments in particulate control, CCC/72
- Wu (2000) Prevention of particulate emissions, CCC/40
- Soud (1995) Developments in particulate control for coal combustion, IEACR/78

NOx control

- Nalbandian (2009) NOx control for coal-fired plant, CCC/157
- Wu (2002) NOx control for pulverised coal-fired power stations, CCC/69
- Nalbandian and Fukasawa (1996) Developments in NOx abatement and control, IEACR/89
- Sloss (1991) NOx emissions from coal combustion, IEACR/36

SO_2 control

- Carpenter (2012) Low water FGD technologies, CCC/210
- Zhu (2010) Non-calcium desulphurisation technologies, CCC/170
- Zhu (2006) Trends in SO_2 emissions, CCC/115
- Fernando (2003) SO_3 issues for coal-fired plant, CCC/72

Multi-pollutants control

- Carpenter (2013) Advances in multi-pollutant control, CCC/227
- Nalbandian (2004) Air pollution control technologies and their interactions, CCC/92

This chapter discusses recent developments in particulate control technologies from a primary $PM_{2.5}$ control angle. Technologies controlling particles with diameters greater than 2.5 μm are not included. The impact that one technology has on other technologies is also not discussed.

For the purpose of this report, the technologies used to control primary $PM_{2.5}$ emissions from coal-fired power plants are classified under the following categories:

- Pre-combustion control
  - Coal type selection
  - Coal preparation
- In-combustion control
  - Optimisation of combustion processes
  - Injection of sorbents into flame zone
- Post-combustion control
  - conventional particle emission control devices (PECD)
  - innovative PECD technologies
  - agglomeration
  - hybrid systems
  - multi-pollutant control systems

Some case studies are used to demonstrate the technologies. For most of the technologies discussed, the fundamentals, such as concept, operation theory, and system components, were covered in detail in previous IEA CCC reports mentioned above, and therefore will not be covered.

4.1 Pre-combustion control

The first place where the formation of fine particulates can be controlled is in the selection of the coal and preparation method.

4.1.1 Coal type selection

Fly ash resistivity plays a key role in the efficiency of $PM_{2.5}$ capture processes. Resistivity is dependent on the flue gas temperature and chemistry, and the chemical composition of the ash itself. Low resistivity fly ash is produced from coals that contain higher sodium levels (Miller, 2015). Also, high coal ash and sulphur contents are related to high values of $PM_{2.5}/PM_{10}$ ratios (Lu and Ren, 2014; Yao and others, 2009). Low sulphur coals contain higher amounts of ash, thus increasing the fly ash loading (Nicol, 2013). Hence, appropriate screening of coal types could reduce the formation of fine PM in power plants. The general method to determine the suitable coal type is a combustion test on a specific furnace. Goto and others (2009a,b) describe a series of modified coal type selection methods, which take into account not only the combustion test results, but also the combustion state in an actual coal-fired power plant.

4.1.2 Coal preparation

The particle size of coal affects PM emissions significantly. Decreasing fineness leads to higher formation of fine PM, because of the direct transfer of more excluded minerals. PM formed during combustion of pulverised coal with a particle size below 63 μm show a bimodal size distribution, including a fine mode at about 0.5 μm resulting from fragmentation of inherent minerals and vaporisation of heavy metals. Larger coal particles (125–250 μm) resulted in a single-mode distribution at about 4 μm (Ninomiya and others, 2004). The finer the pulverised coal, the finer the fly ash, and the large amount of fine particles are in the emitted fly ash (Li and others, 2013). Moreover, combustion of finer coal tends to emit PM containing more volatile trace elements. Therefore, it is important to prepare the coal with appropriate fineness before combustion (Lu and Ren, 2014).

4.2 In-combustion control

In-combustion control to reduce $PM_{2.5}$ emissions can be achieved through controlling the particle fragmentation and the vaporisation of organic matter in the furnace. Usually these are adjusted by optimising the combustion process and injecting sorbents into the furnace.

4.2.1 Combustion optimisation

Optimising the combustion of coal includes adjusting combustion temperature, burning time, and boiler load.

PM emissions increase with increasing temperature of combustion. Li and others (2013) report that the emissions of $PM_{2.5}$ and PM_{10} were the highest at 1100°C. On the one hand, coal particles swell extensively at high temperatures, causing fragmentation and high vaporisation of elements - this favours formation of more fine particles. On the other hand, higher temperatures create a greater possibility of coalescence between small particles to form agglomerated ash, which reduces the amount of fine particles. However, many studies indicate that the overall effect of high temperatures is to increase fine PM emissions. Therefore, under conditions of high coal burnout and high boiler thermal efficiency, it is feasible to reduce the formation and emissions of fine PM by decreasing the combustion temperature or local temperature in the furnace (Lu and Ren, 2014).

The longer the burning time, the more fine PM is produced. This is because longer burning times can cause not only severe fragmentation of coke and minerals, but also a more thorough vaporisation of volatile matter and refractory oxides, which result in the formation of more fine PM. In a furnace, a longer burning time benefits the burnout rate and reduces the unburned carbon content in the resultant fly ash. Hence the optimisation of burning time should consider both PM emissions and combustion efficiency (Lu and Ren, 2014).

As the boiler load drops, air supply and flue gas volume decline and the velocity of flue gas decreases. The large ash particles in the flue gas become more likely to deposit or adhere to the furnace surface. A lower flue gas velocity also increases the efficiency of dust precipitators (Li and others, 2013; Lu and Ren, 2014). Although the emission of total PM could be reduced, a low boiler load results in a larger ratio of fine PM to total particulates. In addition, most of the trace elements tend to deposit on the surface of smaller particles. The smaller the particle, the higher the relative enrichment of trace elements. Hence with deficient oxygen and a short residence time, coal particles in a low load boiler cannot be burned sufficiently, resulting in a higher proportion of fine PM enriched with trace elements after combustion. Thus, high load factors can help with $PM_{2.5}$ emission reduction.

4.2.2 Injection of sorbents into the flame zone

Another effective approach to reduce fine PM formation is to inject high temperature sorbents, such as kaolinite, lime, limestone, silica, and alumina, into the flame zone. Lu and Ren's (2014) work showed that the addition of calcium oxide to pulverised coal could reduce the ratio of fine PM to total particles. In addition, injection of the sorbents could selectively reduce the emissions of metal trace elements, such as lead, sodium, cadmium, copper, beryllium, nickel, and mercury. Under normal combustion conditions, only a small fraction of particles ever has contact with another particle while suspended in the flue gas. But under high temperatures, with the injection of solid sorbents, additional agglomeration between fine coal particles and sorbent particles can occur. Moreover, sorbents with a high porosity provide large surface areas for condensation and further chemical reactions of trace elements into large ash particles. Therefore, as a combined result of physical changes in particles and chemical reactions of trace elements, the injection of sorbents into the furnace zone leads to increasing emissions of coarse PM, while the emissions of fine PM and trace elements are reduced (Lu and Ren, 2014; Yao and others, 2009). This technique has been recommended in the EU BAT for large combustion plants to reduce SOx and dust emissions (European IPPC Bureau, 2015).

4.3 Post-combustion control

After combustion, fine particulates suspended in the flue gas can be captured by a series of physical and chemical methods. Technologies that are effective at controlling fine particulate emissions from coal-fired power plants are well established and already in use on numerous power plants. Major conventional particle emission control devices (PECD) include cyclones, wet scrubbers, electrostatic precipitators, and fabric filters/baghouses. Some technical modifications of conventional PECD have been made to improve $PM_{2.5}$ removal efficiency.

4.3.1 Conventional particle emission control devices

Particulate collection equipment basically consists of gravity settling chambers, impingement separators, cyclones, electrostatic precipitators (ESPs), fabric filters (FFs), and wet collectors/scrubbers. Gravity settling chambers are for large particles. Impingement collecting performance is not sufficient for coal-fired power plants to meet emission standards. Cyclones and wet scrubbers have been used since the early days of emission control to remove particulates but have a low collection efficiency for $PM_{2.5}$. In fact, the US EPA recommended that all industrial and commercial sources currently controlling PM with cyclones or multi-cyclones should upgrade to high efficiency collection devices to collect fine PM (US EPA, 2006). **ESPs** are the dominant PECD and have been used to control particulate emissions from coal-fired power plants for about 60 years. In the 1970s, nearly 90% of US coal-based electric utilities used ESPs. Currently, more than 90% coal-fired power plants in China have ESPs installed. But their $PM_{2.5}$ removal efficiency is low. The $PM_{2.5}$ collection efficiency can reach ~98%, when combined with wet FGD, but this is not high enough to meet the new emission standards. Developed in the 1970s, **fabric filters**, also known as **baghouses**, operate on relatively simple principles compared to ESPs but have a high collection efficiency, 99.9 to 99.99% over a broad range of particle sizes, and ~99.7% for $PM_{2.5}$ (Miller, 1014; Pui and others, 2014).

There has been a trend globally to replace ESPs with FFs in recent years. In America most ESPs are being taken out of service, and replaced with FFs. Indian power plants are looking at converting their existing ESPs into FFs. FFs have been improved to make them more efficient and to extend the operational lifespan of the filter bags. Efforts have been made to increase the number of filters and their depth in order to enlarge the filter in the same sized space. New filter materials are being developed. Traditionally FFs were made of glass, cellulose, and synthetic and polymer fibres. New developments use nanofibre technology, and membrane-type fibres, such as polytetrafluoroethylene (PTFE) (Appleyard, 2015). A review of developments in ESPs and FFs can be found in the IEA CCC reports listed at the beginning of the chapter.

4.3.2 Innovations in PECD technologies

Although conventional PECDs have outstanding performance in the removal of coarse PM from coal combustion flue gas, there are limitations that prevent them from achieving high removal efficiencies for fine particles such as $PM_{2.5}$. During the past decade, some modified technologies based on conventional PECDs have been developed and successfully demonstrated at coal-fired power plants. These developments are introduced in this and the following sections.

Flue gas conditioning

Most of the older ESPs are designed to capture fly ash with a medium resistivity. Collection efficiency decreases when the resistivity becomes too high. However, fly ash resistivity can be decreased and the collection efficiency enhanced by injecting chemical agents and/or water into the flue gas stream to alter the physico-electrical properties of fly ash (Shanthakumar, 2008). This process is called flue gas conditioning (FGC). The most common conditioning agents are sulphur trioxide (SO_3), ammonia (NH_3), and their compounds, and sodium compounds. Sulphur trioxide is widely applied to cold-side ESPs, while sodium compounds are used for hot-side ESPs. An ESP placed after the combustion air pre-heater but before the induced draught fan, and which operates within 130–180°C is known as cold-side ESP. The majority of the installed ESP fleet is cold-side. A hot-side ESP is located before the combustion air preheater and operates at 300–450°C. Sulphur trioxide is by far the most common type of flue gas conditioning, with over 600 installations worldwide. The installation of an SO_3 FGC system is relatively low cost and requires only a short outage period, primarily because the system is not restricted by space on site. While results vary between coals and systems, the injection of 10–20 ppm of SO_3 can reduce the fly ash resistivity to a value that will permit a good collection efficiency. In some cases, the injection of 30–40 ppm of SO_3 has resulted in reductions of fly ash resistivity by 2–3 orders of magnitude. Disadvantages of SO_3 injection systems include the possibility of plume colour degradation, fouling and corrosion. Some are concerned that the use of SO_3 as a conditioning agent (and slip of SO_3 into the treated flue gas) may significantly compromise the performance of a downstream amine-based carbon capture facility. SO_3 is considered to be a 'bad actor' in such a capture facility and may lead to conditions of high amine carryover in the treated flue gas (Oettinger, 2016). Therefore, different FGC chemicals can be favourable. Combined SO_3-NH_3 conditioning is used as the SO_3 adjusts the resistivity downwards while the NH_3 modifies the space-charge effect, improves agglomeration, and reduces rapping re-entrainment losses.

The FGC system requires no modifications to the ESP, but its installation entails a moderate capital cost and an additional operating cost. A short outage is required for the installation of the injection equipment. Previous IEA CCC reports have covered the majority of FGC processes (Fernando, 2003; Nicol, 2013; Wu, 2000; Zhu, 2003). Two recent successful installations are described below.

Chemithon Engineers PvtLtd (CEPL) successfully tested and implemented FGC systems at 23 units at 11 thermal power stations in India during the period 2003-2008 (Trivedi and Phadke, 2008). The change in PM levels before and after FGC were measured during the trial and performance runs. The FGC systems were shown to be a cost-effective and reliable way of reducing fly ash resistivity.

Pentol GmbH has more than 100 SO_3 FGC units operating in Europe (Pentol GmbH, 2015). China Fujian Longking Co Ltd imported their technology and has been installing the system in China since 2006. In 2010, Fujian Longking installed a sulphur trioxide FGC system at Guangdong Pinghai coal-fired power plant. The system has proved to be reliable, with low operating and maintenance costs, and the sulphur trioxide injection rate has been fully automated. The plant can meet ELV of less than 45 mg/m^3 with collection efficiencies peaking at 99.65%, when burning coals that produce highly resistive fly ash (Liu and others, 2008). Also in 2010, Fujian Longking installed another FGC system on Unit 2 of Shannxi Qingshuichuan coal-fired power plant. Both 300 MWe units achieved a 99.80% removal efficiency (Lu and others, 2015).

Improvements to ESP

Considerable research has been put into improving ESP efficiency and the reduction of its power consumption. Some concepts have been developed, including pulse energisation, intermittent energisation, and electrode modified ESP. **Pulse energisation** is where a high-voltage pulse is superimposed on the base voltage to enhance ESP performance during operation under high resistivity conditions. **Intermittent energisation** is where the voltage to the ESP is turned off during selected periods, allowing a longer period between each energisation cycle and limiting the potential for back corona. The ESP can be configured with modified discharge and collection electrodes, which improve the inhomogeneous current distribution of traditional wire-to-plate ESPs and thus provide better control of fine particles (Miller, 2015; Pui and others, 2014).

Electro-mechanical multi-duplex dual-zone ESPs were developed and patented by China Fujian Longking Co Ltd in 2005. This technology separates the charging zone from the collecting zone; both zones have a separate power source, which allows a high voltage direct current (HVDC) of 80 kV to be used without sparking. This technology has a high collection efficiency for PM_{10} and $PM_{2.5}$, for both high and low resistivity fly ash. By 2011, there were 74 electro-mechanical double-zone ESP units installed in China, eight in 660 MWe applications, 42 in 300 MWe and 24 in 300 MWe (Zhang and others, 2011).

Ion Blast is the commercial name and trademark for the ESP developed by GEA Bischoff in Germany. This technology utilises an ionic wind to increase collection efficiency. Ionic wind is the wind produced from the flow of flue gas towards the plate electrodes caused by the macroscopic migration of particulates. The capture of $PM_{2.5}$ should also be increased due to capture in the ionic wind (Seppala and Skroch, 2011).

The **Lentoid ESP** was developed by Wuhan Science and Technology University and Wuhan University in China. The conventional collection plates were replaced by hollow collection electrodes with the holes facing the discharge electrode. Under the lentoid electric field, charged particles are focused into the hollow chambers, undergoing agglomeration by Coulomb force and turbulent flow and enabling a higher collection efficiency. Compared with the conventional designs, this ESP has the electric wind pass through the lentoid electrode, which can decrease the re-entrainment and increase the migration velocity of particles (Lin and Liu, 2011).

Wet ESP (WESP) systems have been in service for more than 30 years to control sulphuric acid and particulate emissions. Thousands of individual WESP modules are currently in worldwide commercial operation. Although operating in the same three-steps as a dry ESP (charging, collecting, and cleaning of the particles from the collecting electrode), a wet ESP washes the collecting electrode with liquid rather than mechanically rapping the collection plates. WESPs can be installed in coal-fired plants after the wet FGD (*see* Figure 11) as a final 'polishing' stage to remove very fine particulates, sulphuric acid and any other mist. Fine particulates are removed more effectively in a WESP because of the humidity in the flue gas stream. Humidity reduces the resistivity of the particle. WESPs continually wet the collection surface and create a dilute slurry that flows down the collecting wall to a recycle tank, preventing the build-up of a layer of particle cake. As a result, captured particulates are not re-entrained and the concentration of fine PM is reduced. Also, when firing low sulphur coal, which produces a high resistivity fly ash, the electrical field does not deteriorate and power levels within a WESP can be higher than in a dry ESP (Lu and Ren, 2014; Miller, 2015; Moretti and Jones, 2012).

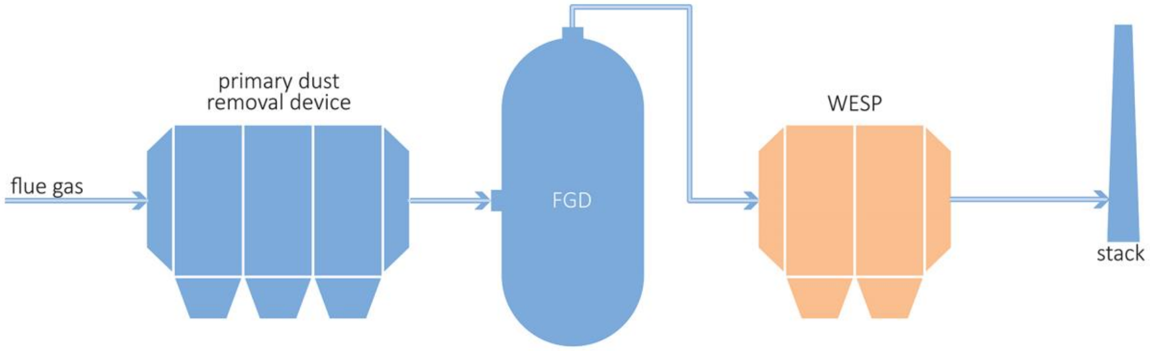

Figure 11 Modification of conventional PECDs with WESP (Lu and Ren, 2014)

Wet ESPs have a number of advantages over dry ones. Firstly, there is no rapping, thus eliminating the emission peaks created during rapping. Secondly, higher corona power can be used to increase charging. Finally, the high humidity lowers the temperature of the flue gas; this increases the specific collection area and lowers fly ash resistivity. WESPs have a high collection efficiency for PM_{10}, $PM_{2.5}$, sulphuric acid and other soluble acid aerosols (Nicol, 2013). They have moderate energy consumption and a robust performance that is unaffected by the properties of the particles (Lu and Ren, 2014). However, water consumption is high and wastewater is generated that requires remediation in complex treatment systems. Flue gas exiting the WESP is cooler than that from a cold-side dry ESP, and this could prove problematic for downstream gas clean-up systems and require the addition of a heat exchanger. In some applications, the sulphur trioxide mist can be at a pH of 0.5 – this is extremely corrosive and will require the WESP materials to be fabricated from corrosion resistant alloys, which are expensive. It is not unusual for a wet ESP to use electrode materials such as Hastelloy® C-276, or 6% Molybdenum (Mo) alloys, while a dry ESP may use carbon steel materials. Continuous and intermittent washing of the wet ESP are the most common types of water washing methods used. Atomized water is continuously sprayed in the gas passage or on the plate to create a film of water on the collector plate during the continuous wash process. This film of water will flow down, keeping the plate wetted to maintain the pH above 5. Spraying water onto the plate electrodes creates mists, which can create a short circuit from the corona discharge to the plate electrodes, and thus adversely affect collection efficiency. A water delivery system that drips water onto the plate electrode can overcome the problem of short circuits, whilst reducing the parasitic load associated with high pressure water (Nicol, 2013; Silva and others, 2015). Major differences between wet and dry ESPs are shown in Table 29.

Table 29 Major design differences between a wet and dry ESP (Silva and others, 2015)

Parameter	Dry ESP	Wet ESP
Gas temperature	121–454°C	48–54°C
Gas humidity	<10% typical	100% (Saturation conditions after wet FGD)
Power density	Variable with coal sulphur content and ash chemistry	Significantly higher than dry ESP
Resistivity	Critical design factor	Not a design factor
Gas velocity	~1.5 m/s	~3 m/s
Treatment time	>10 seconds	~1–5 seconds
Re-entrainment	Important factor	Not a factor
Materials of construction	Mild steel (typical)	Specialty metals, plastic or conductive materials

Historically, WESPs have not been used on large coal-fired power plants. They were mainly used on chemical and mineral facilities to capture fine particulates and acid aerosols. Applications also include wood chip, glass ovens and incineration plants. However, the additional benefits, such as keeping SO_3 at low levels and possible benefits of mercury, NH_3, and HCl control, make WESP a potential choice when considering the available options for fine PM control. WESPs could have favourable economics in smaller scale installations, such as on smaller coal-fired power plant or as an additional fine PM measure to other particulate control devices on larger plants (Seyfert, 2011). WESPs can be designed for either horizontal or vertical flow configurations. The choice of which to use is usually driven by arrangement and cost. Plants with limited footprint areas typically use a vertical design since it takes less space. With no space limitations, the horizontal design is usually preferred as a lower cost option (Silva and others, 2015).

A WESP system was installed after a dry ESP and a wet FGD system at the AES Deepwater high sulphur coal-fired power plant in Texas, USA, in 2008. The collection efficiency of particulates was in the range of 95–97% and for sulphuric acid it was over 90% (Snyder and others, 2008). With no dry ESP installed, the WESP used in unit 1 and 2 at Xcel Energy's Northern States Power Sherco coal-fired power plant achieved a particulate collection efficiency of over 90% and a stack opacity below 10% (Staehle and others, 2003). Amec Foster Wheeler has installed a few WESP systems in coal-fired power plants in America (Amec Foster Wheeler, 2014). For example, a WESP was installed in a 200 MWe unit at Springfield Dallman power plant in 2009, the 750 MWe Unit 2 at LG&E's Trimble County, KY, power station in 2010, and in 2 x 800 MWe units at Peabody Prairie State in Lively Grove, IL, in 2011. China has shown an interest in WESP in recent years. The 350 MWe Unit 4 at Shenhua Guohua Zhoushan 2 power plant has SCR, dry ESP, seawater FGD, and WESP installed by Baoding Meitian Environmental Equipment Co. (www.meitianep.com/shownews1281.html) in June 2014. PM emission is 16.53 mg/m^3 from the dry ESP, 10.76 mg/m^3 from FGD, and 2.55 mg/m^3 from the WESP. Unit 6 at Datang Huangdao coal-fired power plant added a WESP after the FGD system in August 2014. PM emissions from the WESP were 2 mg/m^3. Zhejiang Feida Environmental Science & Technology Co Ltd is another Chinese company manufacturing WESPs. Their latest installation is at the Shenhuan Guohua Sanhe coal-fired power plant. The system started operation on 6 July 2015 and the PM emissions were 0.41 mg/m^3 (Feida, 2015).

With **low temperature ESPs**, the temperature of the flue gas is reduced from 120–160°C to 90–110°C (usually 10°C above the acid dew point) by a low temperature economiser before it enters the ESP. The condensed water from the steam engine exchanges heat with the hot flue gas. Extra heat is transferred to the condensed water to reduce the vapour consumption of the low pressure heater. Due to the lower temperature, the volume of flue gas entering the ESP is reduced, the dust-resistance ratio is decreased, and the precipitation efficiency is increased correspondingly. So utilisation of waste heat and improvement of precipitation efficiency are achieved at the same time. There were three installations of low temperature ESPs on 1000 MW units and one installation on a 600 MW unit in China in 2013. Ultra-low temperature precipitation technology has also been developed, but it is more for the purpose of SOx control (Shu and others, 2013).

Improvements to fabric filters

Although fabric filters have a high dust collection efficiency, they have the following issues:

- pressure losses are significant;
- the collection efficiency for fine particulates, especially PM$_1$ particles, is low; and
- there are blowing leaks during initial operation.

The electrostatically-aided fabric filter deals with these issues by providing an electrostatic charger before the fabric filter (*see* Figure 12). By charging incoming particles using a corona discharge, the collection efficiency of FFs can be increased, particularly for particles in the submicron size range. In addition, the electric forces cause particles to deposit primarily on the surface of FFs, forming dendrite-like structures, which lead to a lower pressure drop and more efficient pulse-jet cleaning (Pui and others, 2014; Tomitatsu, 2013).

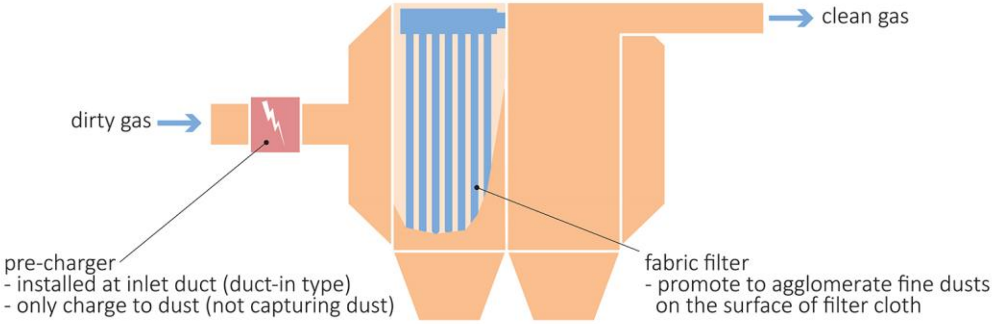

Figure 12 Schematic flow of electrostatic FF (Tomitatsu and others, 2013)

Gas conditioning has also been explored for improving FF performance. Low concentrations of ammonia and/or sulphur trioxide have been added in test programmes to control fine particulate emissions and reduce pressure drop when firing low-rank coals. There are no commercial applications yet (Miller, 2015).

4.3.3 Agglomeration

Using various chemical and physical techniques, agglomeration can bind fine particulates into larger ones, thus making their collection by PECD easier. Some agglomeration techniques have been reviewed by Nicol (2013) and Zhu (2003). The following section describes development in some particle agglomeration techniques since 2003, among which acoustic and electrostatic agglomerators are the most popular.

Acoustic agglomeration

By using high intensity sound waves to improve the turbulence intensity of the gas, acoustic agglomeration can promote collisions between fine particles. It can change the size distribution of fly ash particles in a relatively short time, making them more likely to be captured by the PECD. In the sound field, the orthokinetic and hydrodynamic interactions are believed to be the two most important effects involved in the agglomeration process. The efficiency is affected by many factors such as frequency, sound pressure level (SPL), and the initial aerosol concentration. The majority of the studies on this topic in recent years have been carried out by Chinese researchers. Liu and others (2009) and Zhou and others (2015) found that the optimum operating conditions of acoustic agglomeration can be achieved by adjusting the acoustic frequency, SPL, and residence time. According to orthogonal analysis results from Liu and others (2011), frequency is the dominant factor of coal-fired fly ash acoustic agglomeration and the optimum frequency is 1400 Hz.

Although acoustic agglomeration has been widely studied, the development of this process into an industrial application has been slow. This is probably because of the lack of suitable high-intensity, high-efficiency sound sources and appropriate full-scale agglomeration chambers. The latest trial was carried out by Chen and others (2016). They installed two large agglomerators in the flue gas duct immediately upstream of one of the two ESPs of a 330 MWe coal-fired unit in Leiyang Power Plant, Hunan Province, China. A reduction of 56.7% and 62.3% in volume of $PM_{2.5}$ and PM_{10} in the flue gas, was achieved respectively. The average amount of $PM_{2.5}$ and PM_{10} in hoppers of ESP with acoustic agglomerators increased by around 14% and 10% respectively, in comparison with those of ESP without this technology.

The ash particle removal efficiencies are 99.8% with an acoustic agglomerator and 99.7% without. This demonstrates that fine ash particles in the flue gas can be decreased by the use of acoustic agglomerators.

Electrostatic agglomeration

By utilising a combination of electrostatic agglomeration and electrostatic precipitators, the collection efficiency of conventional PECD for fine sub-micrometre PM can be increased. This renovated type of PECD can be divided into three stages:

- first stage – collecting coarse ash particles and charging the fine particles;
- middle stage – promoting the agglomeration of fine particles by the installation of electrodes that are charged by alternating or direct current voltage
- final stage – collecting the aggregated particles.

Studies show that after applying electrostatic agglomeration, the mass percentage of sub-micrometre size particles in the emissions decreased by 20%, and the collection efficiency of particles in the range of 0.06-12 μm increased to 98% (Watanabe and others, 1995).

Another type of electrostatic agglomeration process with two stages, called the Indigo agglomerator, has been developed by Indigo Technologies of Australia. The system comprises:

- a bipolar charger, which charges half of the dust with a positive charge and half with a negative charge via alternating charged parallel passages; and
- a mixing system, which combines the charged particles from each parallel passage causing the oppositely charged particles to attach to form agglomerates.

The large particles created by this treatment are then easy to capture in the existing particulate control system. The agglomeration system can be retrofitted into existing plants upstream of the dust collection device. This system has been discussed in past IEA CCC reports by Nicol (2013), Sloss (2004), and Zhu (2003) including examples at coal-fired power plants worldwide. A bipolar electrostatic agglomeration system was installed before a conventional ESP in a 300 MW coal-fired unit by a team from Indigo Technologies of Australia in December 2007. Trials burning Chinese and Indonesian coals showed a 30-40% drop in stack PM emissions. By 2008, there were eight commercial installations of the Indigo Agglomerator, in various applications across Australia, the USA and China (Wilkins and others, 2008). Unfortunately, the company was placed into liquidation in February 2011. Yao and others (2009) commented that bipolar electrostatic agglomeration with ESP could be regarded as an alternative to hybrid ESP/FF technology (*see* Section 4.3.4).

Magnetic aggregation

Fly ash particles from coal have a relatively high content of iron oxides, such as Fe_3O_4 and Fe_2O_3. Consequently, these ash particles are easy to magnetise, due to their high saturation magnetisation. Ferromagnetic particles possess remnant magnetisation, which allow them to remain magnetised even after the removal of the external magnetic field. Through a combined effect of magnetic dipole force, Brownian motion, and shear forces, the collision and aggregation between fly ash particles can be enhanced, leading to a transformation from fine to coarse PM (Lu and Ren, 2014). Li and others (2007) carried out an aggregation of coal ash particles in the size range of 0.023–9.32 µm in a gradient magnetic field formed by permanent magnet rings. Results indicated that particles of 0.1–1 µm had higher removal efficiencies than the smaller (<0.1 µm) and bigger (>1 µm) ones. PM capture efficiencies increased with increasing particle mass concentration and particle aggregation time. The technology is not yet commercially available.

Wet agglomeration

Wet agglomeration, or wet granulation, refers to the process of agglomerating particles by spraying liquid binders onto the particles as they are agitated in a fluidised bed, high shear mixer, or similar device. When the liquid binders are sprayed into the agglomerating zone, they collide with dry particles and are distributed throughout them. Then the binders begin to wet the particles, forming the initial agglomerates. As the wetting process proceeds, the fluid penetrates into the pores of the particle surface, forms a nucleus, and migrates outward as the nucleus grows. Further growth of agglomerates occurs when fine particles collide with them and adhere to the surface. Therefore, through a combined effect of wetting, nucleation, and growth, the particle size distribution can be changed into a coarse mode, which is of benefit to the ultimate PM removal process. Application of wet agglomeration in a circulating fluidised bed (CFB) is thought to be a feasible and promising approach for fine PM control because of its ability to remove both sulphur dioxide and fly ash (Lu and Ren, 2014)

Thermophoretic deposition

Particle thermophoretic deposition in gas flowing over tube surfaces is an old technology. Zhou and others (2005) from Tsinghua University China carried out a series of experiments to study particle deposition behaviour in a rectangular channel with a designed temperature gradient. Phase Doppler anemometry was used to measure the distribution and concentration of fine particles. As the ratio of the inlet temperature to the cool wall temperature increased from 1.35 to 1.60, the capture efficiency by the wall increased from 7.5% to 12.5%. An empirical correlation was developed for calculating the efficiency of the thermophoresis deposition based on the experiments. Furthermore, the concept of potential capacity and its variation was adopted to establish a model to analyse the $PM_{2.5}$ thermophoretic deposition efficiency (Yao and others, 2009). However, no further work has been found in the literature.

4.3.4 Hybrid systems

The most common hybrid systems are the combination of electrostatic precipitation with fabric filtration to benefit from the advantages of both technologies. There are several hybrid systems that have been developed, namely the Advanced Hybrid Collector (AHPC), Compact Hybrid Particulate Collector (COHPAC), Electrostatically stimulated fabric filter (ESFF) – Max-9™, Multi-stage Collector (MSC), Electrostatic Fabric Integrated Collector (EFIC) and ESP-FF hybrid system (EFF). Of these, COHPAC, EFIC, and EFF are commercially available. There are also other types of combinations of two or more PECDs, such as electro-cyclone and electro-scrubber.

Compact Hybrid Particulate Collector (COHPAC)

The Compact Hybrid Particulate Collector was developed and patented by Electric Power Research Institute (EPRI), in the USA, in 1991. This technology has been reviewed by IEA CCC (Nicol, 2013; Zhu, 2003). The fabric filter is located in a separate casing downstream of the ESP (known as COHPAC I) or within the existing ESP's casing by replacing one or more fields of collecting plates with fabric filter modules (COHPAC II) (*see* Figure 13). Since the pulse-jet collector operates as a polisher to achieve lower emissions of particulates, the low dust loading to the baghouse enables the filter to be operated at high air-to-cloth (A/C) ratios (17.7 m/min), allowing a small footprint on-site, longer bag life, lower pressure drops, and lower parasitic load. The system can be retrofitted on existing units and achieve high PM removal efficiencies at relatively low cost (Miller, 2015).

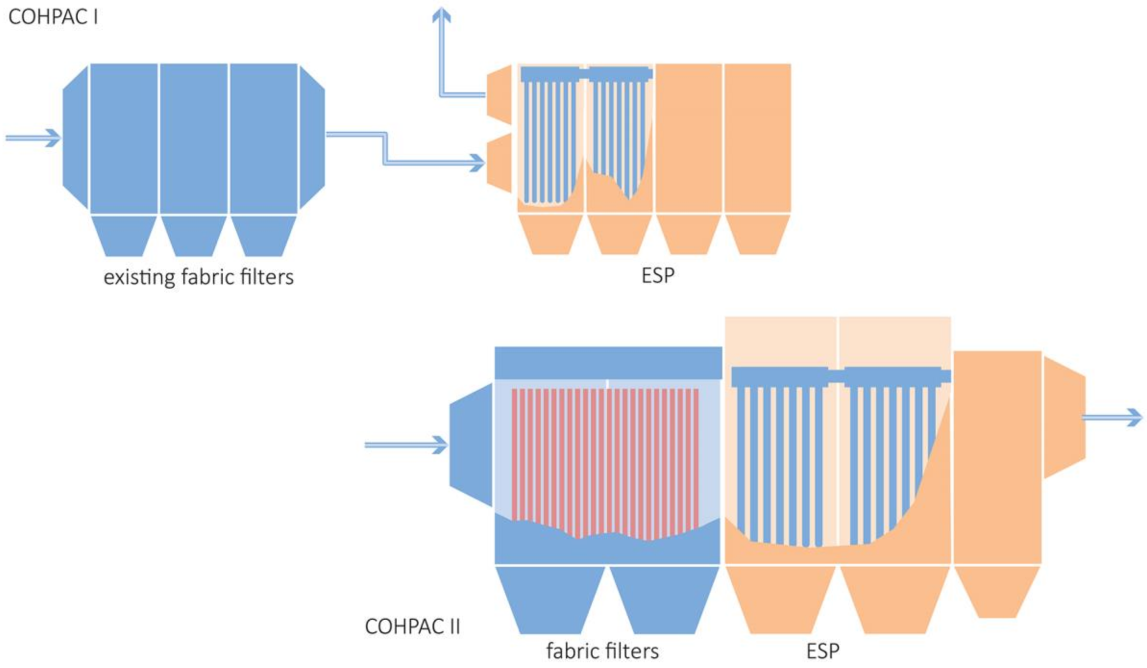

Figure 13 Schematics of COHPAC and COHPAC II (www.hamonusa.com)

Full-scale demonstrations of COHPAC technology were conducted at the 272 MWe Unit 3 of E.C. Gaston low sulphur coal-fired power plant and 2 x 575 MWe units at the Big Brown Plant. Results from COHPAC operations have been positive, achieving 99.9% collection efficiencies, allowing fuel flexibility, reducing opacity, increasing bag filter life, and decreasing operating costs. This has led to units being installed commercially since 2000.

EPRI further developed COHPAC by coupling it with a sorbent injection system upstream of the FF. This technology is called TOXECON™. Carpenter (2013) included this technology in her multi pollutant control report (*see* section 4.3.5).

Hamon Research-Cottrell (www.hamonusa.com) is a licensed supplier of EPRI's COHPAC™ and TOXECON™ systems. To date, Hamon Research-Cottrell has installed over 1,700 MW of COHPAC™ systems, on both coal-fired boilers and waste-to-energy incinerators.

Electrostatic-Fabric Integrated Collector (EFIC)

The Electrostatic-Fabric Integrated Collector (EFIC) developed by China Fujian Longking is similar to COHPAC II in that the ESP fields are removed and replaced with a pulse jet fabric filter system. The system includes pulsing valves, step-down arrangement of bag compartments, sizing of clean air chamber exit valves, a large clean gas chamber, and a filter bag bypass system for online overhaul. Utilising electric fields causes particle agglomeration and enables easier capture. EFIC can effectively avoid the pressure drop caused by the fine particles penetrating into the bag so that the $PM_{2.5}$ particle collection efficiency is improved (Huang and others, 2013).

The first EFIC was installed in the last three fields of a four-field ESP on a 660 MWe unit at the Boasham coal-fired power plant in 2009 in China (*see* Figure 14). Historical ESP efficiencies averaged 80% due to varying coal types. After the retrofit, EFIC collection efficiency reached 99.8% (30 mg/m^3 outlet emission) with low pressure drops of 900–1000 Pa, and a lower parasitic load. According to its website (http://www.longking.com.cn) (December 2015) Fujian Longking had successfully installed EFIC on nine 600 MWe units, forty 300 MWe units, and forty units below 300 MWe. Fifty units are currently in operation.

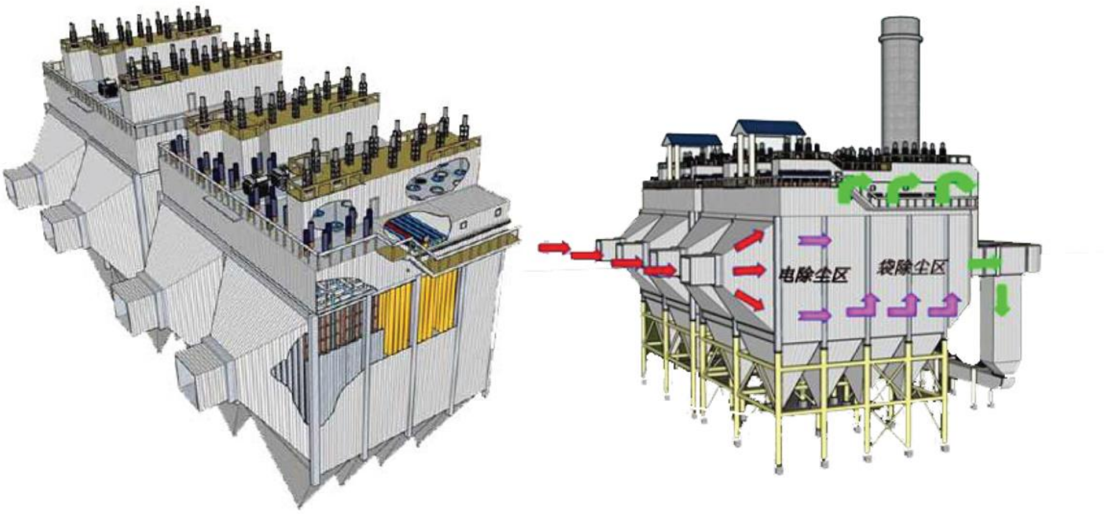

Figure 14 Schematic of EFIC installed at Baoshan power plant (www.longking.com.cn)

ESP-FF hybrid system (EFF)

Zhejiang Feida Environmental Science & Technology Co Ltd developed an ESP-FF hybrid system (EFF), which has a split level filter. This special design can even out gas flow inside an ESP, improve the dust cleaning efficiency of fabric filters and fundamentally change the conventional flue gas guidance pattern. Stable and long term operation with high efficiency and low resistivity has been achieved. Feida's EFF has two types: integrated and separated. The integrated type has the ESP and FF in one case, with a direct connection between the two elements. The dust collector is separated into several passages; each chamber has an exit damper. In the separated type, the ESP and FF are connected by a duct, and the FF area acts as the independent dust collector consisting of several separated chambers. Each chamber is designed with a built-in bypass duct, and entrance and exit dampers (Feida, 2015; Zhu and others, 2013).

Feida's first EFF system was installed at the Tianjin Chentang coal-fired power plant achieving PM emissions of 5 mg/m^3. Feida also installed EFF at the Huaneng Taichang 630 MWe, Tianjiaan 300 MWe in China and at the Anpeila 2 x 600 MWe coal-fired power plant in India (*see* Figure 15).

Figure 15 Feida EFF system at Huaneng Taichang, left, and Anpeila, right, power plants (www.feida.biz)

Advanced Hybrid Collector (AHPC)

AHPC was developed in the late 1990s by the Energy and Environmental Research Center at the University of North Dakota, USA, with funding from US DOE. The FF and ESP are integrated into the same unit, providing a collection efficiency of >99.99% for all particle sizes ranging from 0.01 to 50 µm. Details of this technology are described by Sloss (2004) and Zhu (2003). Following a successful pilot test in 2001, the US DOE funded a full-scale AHPC demonstration at the Big Stone coal-fired power plant from 2002 to 2004 under the DOE Power Plant Initiative Program. Initially the AHPC achieved good results. However, problems were soon encountered with high pressure drops, bag failure within six months, and emissions and opacity limits not being met due to the bag failure. The reason for these problems is that high resistivity ash was not eliminated which severely limited the effectiveness of the electrostatic zone. Big Stone decided to replace the AHPC with a new pulse jet fabric filter (PJFF) (Lugar, 2010). The technology has not received funding for further development since 2004.

Electrostatically stimulated fabric filter (ESFF) – Max-9™

The electrostatically stimulated fabric filter (ESFF) is patented by the US EPA. General Electric is the exclusive licensee for the ESFF, marketed as Max-9™. The operating and cleaning principles are exactly the same as a FF, but with the addition of an electrostatic charge for enhanced collection. It combines high voltage discharge electrodes and fabric filters in a common casing. When installed after a particulate control device, Max-9™ can be used as a polishing filter for fine particulates and for mercury removal.

An existing pilot-scale FF at Unit 2 of Alabama Power Company's Plant Miller in the USA was adapted to continue the development of ESFF. Figure 16 shows the layout of the ESFF installation. Collection efficiencies of 99.99% of particulates were achieved in the field tests. No further information about any commercial scale installations can be found.

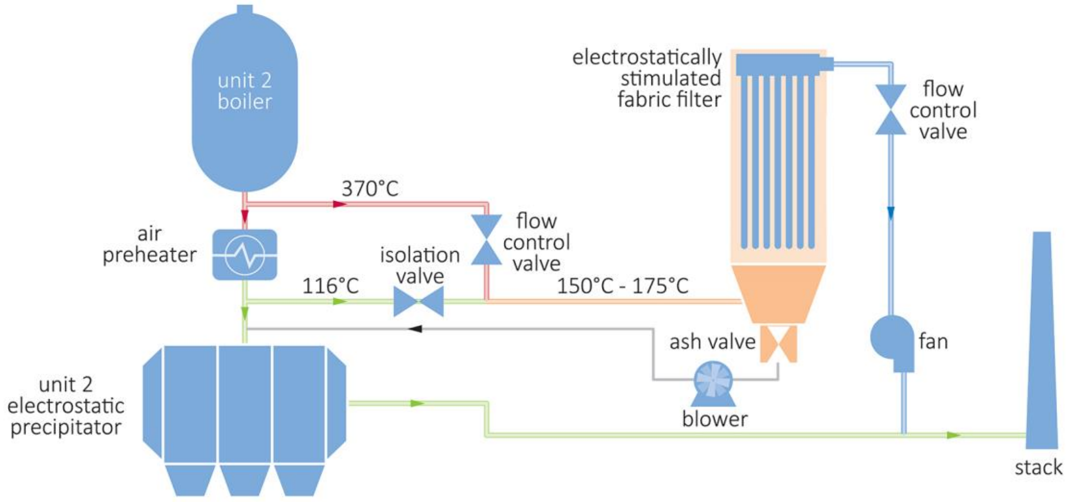

Figure 16 Schematic representation of the ESFF installation at Plant Miller (Heaphy and others, 2004)

Multi-Stage Collector (MSC)

The Multi-Stage Collector was developed by Allied Environmental Technologies Inc, USA, and is described by Zhu (2003). The MSC combines a single-stage and two-stage ESP with barrier filtration. The MSC collection efficiency is independent of fly ash resistivity and has a high collection efficiency of $PM_{2.5}$. In 2006, a proof-of-concept pilot demonstration for the technology was completed. Initial results showed a collection efficiency of 99.99% at face velocities of approximately 0.04 m/s. Another advantage of the MSC is that particulates will not follow the gas streamlines that cut past the filter cake, but instead follow the electric field lines which direct the particulates into the filter cake. Allied Environmental Technologies has been unable to find a sponsor for a full-scale demonstration (Nicol, 2013).

Other types of hybrid systems

A cyclone is a simple dust control device, which is cost efficient to construct, operate, and maintain but has a low collection efficiency for $PM_{2.5}$. By combining ESPs and cyclones, **electro-cyclones** have been developed to control fine particles efficiently without an increase in pressure drop and capital costs. In an electro-cyclone, a high voltage is applied to a discharge electrode or vortex finder, which is installed in the central axis of the cyclone to generate corona ions and electrostatic forces. When particles are introduced into the electro-cyclones, they are charged by diffusion and field charging mechanisms and then driven to the collection wall by electrostatic forces in conjunction with centrifugal forces. Particles are collected mainly through two mechanisms, namely, centrifugal forces for large particles and electrostatic forces for small ones. However, there is usually a trade-off between the two mechanisms in real applications. Increasing the flow rate decreases residence time and electrostatic effects, thus leading to a small enhancement of $PM_{2.5}$ collection. On the other hand, if the gas velocity is too low, the collection efficiency of large particles decreases. This trade-off often makes electro-cyclones of little practical value in large-scale applications (Pui and others, 2014). Lin and others (2013) attempted to combine a wet ESP with a cyclone. A continuous cleaning water flow is supplied to prevent the deposition and accumulation of particles on the collection electrode surfaces and particle re-entrainment caused by rapping. Research is still at an early stage but preliminary results show promise with improved collection of fine particles.

Jaworek and his colleagues (2006) have described an **electro-scrubber**, which combines the advantages of electrostatic precipitators and wet scrubbers. Unlike conventional wet scrubbers, electro-scrubbers use spray droplets that are charged by corona discharges, induction, and electrosprays. Due to the additional electrostatic attraction/repulsion forces between dust particles and charged scrubbing droplets, electro-scrubbers have a high collection efficiency, especially for PM_1 particles. Compared with conventional wet scrubbers, they are also cheaper to operate, due to the lower water consumption and pressure drop. Because of these advantages, they have been recommended as a complementary PECD following the last stage of a conventional ESP to help remove submicron particles (Pui and others, 2014). However, no pilot or demonstration scale test can be found for this technique.

4.3.5 Multi-pollutant control systems

Many coal-fired units now have a combination of pollution control equipment fitted. Together, these systems can reduce emissions of both primary and secondary $PM_{2.5}$ significantly. Multi-pollutant systems remove two or more pollutants in a single reactor or a single system designed for the purpose. They can have lower capital and operating costs than a series of traditional systems to remove the same number of pollutants. Their footprint is often smaller than conventional single pollutant counterparts treating a similar volume of flue gas, making them easier to install in retrofit applications. IEA CCC has produced reports on this fast developing topic, most recently in 2013 by Carpenter. This section abstracts a few examples from her report which are relevant to $PM_{2.5}$ emissions. Developments since 2013 are included.

TOXECON™ (toxic emission control process)

EPRI has developed two technologies, TOXECON™ and TOXECON II™, for removing mercury and fine particulates. As mentioned previously in Section 4.3.4, TOXECON™ consists of a sorbent injection system and a compact pulse jet fabric filter, where the sorbent is injected into the duct before the fabric filter. In TOXECON II™, the sorbent is injected into the back portion of a cold-side ESP. The TOXECON process is suitable for many existing plants where new emissions regulations are pushing the existing ESPs beyond their capabilities. It offers some of the benefits of COHPAC™ but at a lower capital cost. In both technologies, fine solid particulates ($PM_{2.5}$) are effectively controlled with the addition of a polishing fabric filter. Sorbent can be added for acid gas control such as H_2SO_4 ($PM_{2.5}$ aerosol). TOXECON™ has been installed at eight plants. Two of the installations are described by Snyder and Wise (2015). Licensed suppliers of the TOXECON™ technologies include Babcock & Wilcox and Hamon Research-Cottrell.

ECO® technology

Powerspan's Electro-Catalytic Oxidation (ECO®) technology is an integrated process that removes NOx, SO_2, SO_3, HCl and other acid gases, mercury and other heavy metals, and fine particulate matter in a single system. This is achieved in three steps by using a dielectric barrier discharge (DBD) reactor, an ammonia-based scrubber and a wet ESP. The flue gas then enters the integral wet ESP where aerosols created in the discharge reactor and ammonia scrubbing process steps, along with mercury, other air toxics and fine particulate matter, are captured and returned to the lower loop. The clean flue gas is emitted to the atmosphere through the wet stack or sent on to an ECO_2® unit to remove carbon dioxide. The ECO®

technology removes significant amounts of the criteria pollutants SO_2, NOx, mercury, $PM_{2.5}$ and acid gases, in most cases, to below the regulated limits.

The first demonstration of the ECO® process was built at First Energy's R E Burger coal-fired power plant at Shadyside, OH, USA. The ECO® unit treated a 50 MWe (equivalent) slipstream from a 156 MW front wall boiler from February 2004 to December 2010. The ECO_2® technology was tested on a 1.3 MWe slipstream from the 50 MWe ECO® unit from December 2008 to 2010. Over 90% NOx, >98% SO_2, 85% oxidised mercury and 10 mg/m^3 particulate matter were achieved over six months of testing of the ECO® system. None of the ECO® technologies have yet been demonstrated at full-scale on a coal-fired power plant.

4.4 Comments

Both ESPs and FFs can efficiently remove fine particulates from coal-fired power plants and control PM concentration at the stack below 20 mg/m^3, with efficiency ranging from 90% to 99.9%. In order to improve the performance of ESPs, a number of innovations have been developed. For example, China Fujian Longking's FGC treatment increased ESP efficiency at the Shanxi Qingshuichuan coal-fired power plant to 99.8%. Using a WESP after a dry ESP and wet FGD system, the American AES Deepwater Power Plant achieved 97% removal efficiency for fine particulates. PM emissions from Chinese coal-fired power plants with WESP installed are reduced to as low as 0.41 mg/m^3, well below their new strict emission regulation limit of 10 mg/m^3. Hybrid systems have also improved fine PM emission control. For example, COHPAC achieved a 99.9% collection efficiency at the Big Brown power plant in the USA. China Fujian Longking's EFIC has a collection efficiency of 99.8% and Feida's EFF at Tianjin Chentang power plant has limited PM emissions to 5 mg/m^3. Therefore, with current available emission control technologies, the emission standards for $PM_{2.5}$ can be achieved.

5 Discussion and conclusions

$PM_{2.5}$ are generally classified into primary and secondary particles. Primary $PM_{2.5}$ particles are those that are directly emitted to the air. Secondary $PM_{2.5}$ particles are formed from gaseous pollutants, such as SOx, NOx, NH_3, and VOCs, through nucleation, condensation, coagulation and evaporation of water droplets in which the gases have dissolved and reacted. Secondary sulphate and nitrate particles formed from SOx or NOx precursors are usually the dominant component in $PM_{2.5}$ particles. However, when measuring $PM_{2.5}$, both the International Organization for Standardization (ISO) and US Environmental Protection Agency (EPA) classify primary $PM_{2.5}$ into filterable and condensable components.

During the last decade, regulations on $PM_{2.5}$ emissions have been implemented around the world. After the World Health Organisation (WHO) issued a guideline in 2005, $PM_{2.5}$ emission limits have been included in the air quality standards of most countries. However, all the countries covered in this report regulate $PM_{2.5}$ from coal-fired power plant as part of particulate matter, that is, including PM_{10}. This includes China which has recently taken more interest in $PM_{2.5}$ because of the smog problems in its cities.

The monitoring time periods and reference conditions for $PM_{2.5}$ emission limit values (ELVs) vary from country to country. Different countries also use different units for the ELVs. This makes it difficult to compare emission standards. Although China's air quality standards for $PM_{2.5}$ and its precursors are less strict than WHO's guidelines and the European Union standards, it has stricter PM emission limits for new coal-fired power plants. This is a challenge for plant operators as the current available emission control technologies have to operate at an optimum level or update to new technologies in order to meet the PM limit of under 10 mg/m^3.

The most commonly used $PM_{2.5}$ measuring methods were developed by the US EPA. Their methods 201A and 202 were promulgated in the early 1990s for PM_{10}. They were revised in 2010 by adding $PM_{2.5}$ measurements. The ISO also issued three testing and measuring standards over 2009, 2012 and 2013. Canada developed their own three measuring methods for $PM_{2.5}$ emissions in 2013. Other countries are using either the US EPA or ISO methods. Further work is required to globally standardise the measuring methods so that research results from different countries can be accurately compared.

The majority of fine PM testing and measuring methods, such as those mentioned above, concentrate on determining the total mass of $PM_{2.5}$. High quality and comprehensive measurement methods for the determination of the chemical components of $PM_{2.5}$ need to be developed. Since the chemical composition of $PM_{2.5}$ is still not completely understood, a full chemical analysis of $PM_{2.5}$ remains a challenge.

$PM_{2.5}$ emissions from coal-fired power plants can be controlled before, during and after combustion. Pre-combustion, that is, choosing a suitable coal type can be carried out through a combustion test on a specific furnace. Fine pulverised coal tends to emit more fine ash than coarser particles. Therefore, burning coal with the appropriate fineness can help mitigate $PM_{2.5}$ emissions. Optimising combustion temperature, burning time, and boiler load can reduce the formation and emission of fine PM. A low boiler load generates a larger ratio of fine PM to total particulates. Consequently, avoiding low load conditions can help reduce $PM_{2.5}$ emissions. However, post-combustion control systems are needed to meet emission limit regulations.

Electrostatic precipitators (ESP) and fabric filters (FF) are the two most commonly used conventional particulate emission control devices. An ESP can collect 98% of $PM_{2.5}$ when combined with flue gas desulphurisation (FGD) and/or other pollutant control systems. But FFs are becoming more popular since they are relatively simple to operate and have a higher collection efficiency – up to ~99.7% for $PM_{2.5}$.

In order to improve the removal efficiency of ESPs, several innovations have been made. Of these, flue gas conditioning (FGC) and wet ESPs (WESP) are the most successful. Injecting chemical agents and/or water or steam into the flue gas steam can alter the physico-electrical properties of fly ash, consequently reducing fly ash resistivity. The most common conditioning agents are sulphur trioxide, ammonia, and sodium compounds. The SO_3 FGC system is relatively easy to retrofit as it has a small footprint and a low capital cost, and only a short outage period is needed for its installation. But use of SO_3 for $PM_{2.5}$ control is not recommended if an amine-based carbon capture is contemplated in the future from the modified facility. There are over 600 FGC installations worldwide.

The removal efficiency for fine particles can be improved by employing a WESP after the FGD system. Additional benefits such as keeping SO_3 at a low level and capturing mercury, NH_3, and HCl can make WESPs a desirable choice when considering the available options for fine PM control. WESPs could have favourable economics for smaller coal-fired power plants or act as a final polishing stage on larger plants. There are numerous WESP installations, especially in China.

Low temperature ESPs have drawn attention in recent years, especially ultra-low temperature precipitation technology, which has the co-benefit of SOx control.

Agglomeration can bind fine particulates into larger ones, thus making their collection easier. Acoustic and electrostatic agglomerators have been studied the most. The development of acoustic agglomeration into an industrial application has been slow. This is probably because of the lack of a suitable high-intensity, high-efficiency sound source and appropriate full-scale agglomeration chambers. A two-stage electrostatic agglomeration process was developed by Indigo Technologies of Australia, and installed on several power plants in Australia, the USA and China. Unfortunately, the company has gone into liquidation.

Hybrid systems combine the advantages of ESP and FF. This technology has improved PM collection efficiency to 99.99%. The US EPRI's Compact Hybrid Particulate Collector (COHPAC), China Fujian Longking's Electrostatic Fabric Integrated Collector (EFIC), and China Feida's ESP-FF hybrid system (EFF) are all commercially available. The Advanced Hybrid Collector (AHPC), Electrostatically Stimulated Fabric Filter, and Multi-Stage Collector (MSC) all have promise but need further investment and demonstration trials before they can be brought to the market.

Multi-pollutant control systems that include a FF or ESP element are commercially available. As well as achieving a high $PM_{2.5}$ collection efficiency, they can capture additional pollutants and can have lower capital and operating costs than a series of traditional systems to remove the same number of pollutants. Commercially available technologies with the most benefit for fine particulate control are the TOXECON™ and ECO® systems.

In the early 1990s, the USA led the world in $PM_{2.5}$ research. As a result, $PM_{2.5}$ was first regulated in this country and technologies developed for its control. In the last decade, China has renewed interest in $PM_{2.5}$. They have carried out a large amount of research, and imported and made innovations to a number of technologies for emissions control. China has also developed and installed a number of modern technologies, such as flue gas conditioning and hybrid ESP/FF systems. About 90% of the literature on $PM_{2.5}$. published since 2010 originated in China. This obviously shows the Chinese determination to control $PM_{2.5}$ emissions and clean the air. However, China still has a huge air pollution problem. Beijing issued its first 'red' air pollution alert on 7 December 2015, suspending schools, restricting car travel and banning outdoor barbecuing and fireworks.

There are no miracle technologies for $PM_{2.5}$ emission control. Individual coal-fired power plants vary in aspects, such as type of coal used, location, water resources, space availability, funding and local labour cost. Consequently, performance from a certain particulate control technology on a specific plant may not be achieved on other plants. However, providing correct assessments and management are undertaken, the emission standards set up by each country and region will be achievable with currently available pollution control technologies.

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