Chapter 4
Atmospheric Emissions from Thermal (Coal-Fired) Power Plants and Associated Environmental Impacts

Gyanesh Kumar Singh, Pradhi Rajeev, Debajyoti Paul and Tarun Gupta

Abstract Power plants, which are major point source of air pollutants, contribute significantly to the overall ambient air particulate matter (PM) loading. Due to low grade of coal utilized in the power plants, emitted gases and PM affect the environment as well as public health. Gaseous as well as particulate emissions from power plants depend on types of coal and combustion conditions. Coal is subjected to various processes from arrival up to the combustion in a power plant. Particle size distribution and composition of PM emitted by coal combustion sources vary according to various formation and transformation processes to which they are subjected during their lifetime such as grade of coal, pulverization, and storage and combustion conditions including type of boiler, etc. Gaseous emissions in large amount from stack of power plants include gases such as sulfur dioxide, carbon monoxide, oxides of nitrogen, carbon dioxide, and volatile organic compounds. Respirable particulate matter is also emitted at a large scale in the form of fly ash, bottom ash, and flue gas. Toxicity associated with suspended PM can deteriorate human health by penetrating and affecting human respiratory system. Apart from this, these emissions can alter the atmospheric radiation balance by inducing climate forcing, and provide excess condensation nuclei for fog and cloud formation, thereby significantly altering the regional level weather conditions and patterns. Advanced techniques to track the precursors of PM such as stable isotope analysis and metal identification along with various modeling methods can be used quite effectively for understanding the sources and health hazards related to power plants. These mechanisms can be understood by making use of a tracer (such as stable isotope ratios, for example, $\delta^{13}C$ or elemental ratios), which can track down the PM formation processes either in the stack exiting flue gases or further downstream from the source. Emissions from coal-fired power plants also contain certain toxic trace metals, which can severely affect the health of general public.

G. K. Singh (✉) · P. Rajeev · T. Gupta
Department of Civil Engineering, Indian Institute of Technology Kanpur, Kanpur, India
e-mail: gyanesh@iitk.ac.in

D. Paul
Department of Earth Sciences, Indian Institute of Technology Kanpur, Kanpur, India

4.1 Introduction

Most of the electricity demand in India is primarily met by coal-fired power plants and the resulting pollution is a severe cause of concern with respect to ambient air quality. One of the major fossil fuels used for electric power generation worldwide is coal, which satisfies nearly 40% of the electricity demand (Energy Information Administration, EIA 2013). In India during 1990s, electric power generation from thermal power plants was estimated to have contributed about 96% of total carbon dioxide (CO_2) emissions (ALGAS 1998), while it was reported ∼62% in 1994 (NATCOM 2004) and 69% in 2007 of the total CO_2-equivalent emissions from energy sector (INCCA 2010; Mittal et al. 2012).

Coal is a heterogeneous, complex, and variable substance that contains mineral inclusions in addition to the fossilized carbonaceous material (Flagan and Seinfeld 2012). Coal is generally classified based on percentage of carbon content, its calorific value, and sulfur content. General classification of Indian coals is presented in Table 4.1. The composition of coal is normally reported in terms of proximate analysis (fixed carbon, volatile matter, moisture, and ash, all in weight %) and ultimate analysis (elemental composition of carbon, hydrogen, nitrogen, oxygen, and sulfur, all in weight %) (Francis 1961; Whitehurst et al. 1980; Bustin et al. 1993).

Since coal-fired power plants (Fig. 4.1) are the cheapest source for producing per kWh of electricity, therefore, there is an expansion in construction of such power plants. Most of the coal consumption occurs in countries such as India, China, and US, which own nearly half of the worldwide coal reserves (Conti et al. 2016). Environment and human health are at risk owing to the emissions caused by thermal (coal-fired) power generation. In addition to CO_2 emissions, the pollutants that are released from combustion of coal include particulate matter (PM), sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen oxides (NO_x), volatile organic compounds (VOCs), and various trace metals such as mercury, arsenic, cadmium, selenium, etc. Emission of large amounts of CO_2 can affect the global atmospheric radiative balance and in turn leads to global warming and associated climatic changes. SO_2 emitted is a precursor of acid rain and secondary fine PM, whereas NO_x can significantly affect the tropospheric ozone chemistry. Previous studies have shown that submicron particles from coal combustion can be formed through vaporization, condensation, and nucleation. On the other hand, larger sized particles can be formed from fragmentation and coagulation (Ninomiya et al. 2004). PM emissions from coal-based power plants are high in countries such as India and China due to the low thermal efficiency of boiler and usage of lower grade coal resulting in severe air pollution.

Table 4.1 General classification of Indian coals (IS: 770-1794) (Classification and Codification of Indian Coals and Lignites 1977)

| Type	Name	Symbol	Volatile matter % at 900 ± 15 °C (Unit coal basis)	Gross calorific value (kcal/kg)	Chief uses
Anthracite	Anthracite	A_1	3–10	8330–8670	Gasification, producers, domestic, where intense heating is not required
	Semi-anthracite	A_2	10–15	8440–8780	
Bituminous	Low-volatile (caking)	B_1	15–20	8670–8890	Carbonization for the production of metallurgical coke
	Medium-volatile (caking)	B_2	20–32	8440–8780	
	High-volatile (caking)	B_3	Over 32	8280–8610	Coking coals, gasification
	High-volatile (semi-caking)	B_4	Over 32	8000–8440	Log-flame heating
	High-volatile (noncaking)	B_5	Over 32	7500–8060	Steam raising, gasification, long flame heating
Sub-bituminous	Noncaking	B_6	Over 32	6940–7500	Steam raising, gasification
Lignites or brown coal	Normal lignite	L_1	45–55	6110–6940	Steam raising, briquetting
	Canneloid	L_2	55–65	6940–7500	
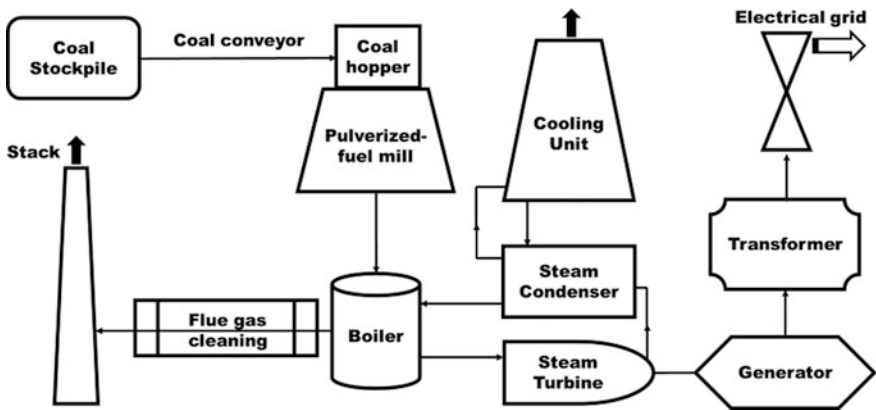
Fig. 4.1 Flowchart of a typical thermal power plant (inspired by Davis 2000; Buhre et al. 2005; Chawla et al. 2011; Park et al. 2018)

Since finer fractions of atmospheric PM including emissions from thermal power plants have longer residence time in the ambient atmosphere, therefore, they can cause respiratory problems to population residing even far off from such sources as they can penetrate deeper into the lungs. Adverse health effects can be caused by the toxic elements that are released from coal combustion such as copper (Cu), cadmium (Cd), arsenic (As), cobalt (Co), chromium (Cr), manganese (Mn), selenium (Se), lead (Pb), iron (Fe), mercury (Hg), nickel (Ni), vanadium (V), and zinc (Zn) in particle or gaseous form (Linak et al. 2000; Lighty et al. 2000; Huggins et al. 2004; Reddy et al. 2005; Cordoba et al. 2012). Significant amount of mercury (Hg) is emitted from coal combustion, which is toxic and hazardous and it can enter into the food chain causing fatal diseases. Apart from the chemical constituents, PM_{10} (particles having aerodynamic diameter ≤ 10 μm) and $PM_{2.5}$ (particles having aerodynamic diameter ≤ 2.5 μm) also possess a critical health hazard as they are inhalable and can deeply penetrate into the lungs causing respiratory illness and cardiovascular diseases (Pope et al. 1995). Interdependence of PM with mortality and daily morbidity has been reported by previous studies due to deteriorating heart and lung functions (Dockery et al. 1993; Pope et al. 1995, 2004; Jerret et al. 2005). Fly ash and coal dust in millions of tons are emitted annually during coal combustion that results in the formation of PM, which also possess a life expectancy risk (Chen et al. 2004; Clancy et al. 2002; Pope et al. 2009). During high exposure events, co-pollutants (gaseous) also have an effect on the cardiopulmonary system (Chen et al. 2005; Samoli et al. 2006; Ackermann-Liebrich et al. 2007; Arif and Shah 2007). In post-combustion phase, PM toxicity is increased due to the presence of polycyclic aromatic hydrocarbons (PAHs) and metal content (Bostrom et al. 2002). Health effects due to primary particle emissions from coal, which has been widely studied by many researchers, and additionally a study titled "Toxicological Evaluation of Realistic Emission Source Aerosols" (TERESA) reported adverse effects due to exposure, created under various simulated atmospheric conditions, from secondary emissions of coal combustion (Ruiz et al. 2007a; Diaz et al. 2011; Lemos et al. 2011; Wellenius et al. 2011; Godleski et al. 2011). Various control strategies have been successfully applied over the years in past to limit emissions but still coal combustion is relatively important source of some trace elements, especially mercury (Sloss 2002). Present pollution control equipment for power plant emissions is effective in reducing major trace element emissions but fail to capture more volatile trace elements (Sloss 2002). Policymakers need to consider the environmental degradation potential of coal-based power plants and policy frameworks should be formed to control these emissions. Presently, the methods and technology to reduce the emissions include electrostatic precipitators (ESP), flue gas desulfurization, dry sorbent injection (DSI), fabric filters, selective catalytic reduction (SCR) methods, and mercury control methods (MCM) (Baig and Yousaf 2017). Also, efforts should be made to reduce the dependence on coal-based power plants for electricity generation and use of renewable sources should be promoted. With the increase in the environmental degradation, power plants will face more stringent governmental pollution norms in the near future. National and international regulations should be improved to control trace element emissions and avoid uncertain risks.

In this chapter, we have discussed the processes occurring in power plants which are responsible for large-scale emissions that elevate the gaseous and particulate matter concentrations in the atmosphere. The types of coal used in power plants, their characteristics, conditioning and pulverization, role of boilers, and subsequent by-products formed (fly ash) during the combustion process have been presented. Control measures are adopted for the reduction of emissions like installation of electrostatic precipitators, and stack sampling required to govern the total contribution to air pollutants has also been discussed. The chapter also highlights the characteristics of the gaseous and particulate matter from coal-based power plants and their impact on the atmospheric processes and human health. Eventually, the estimation of emissions from this particular source into the atmosphere has been discussed as it is crucial for understanding the contribution from this particular source to atmospheric loading and to undertake preventive actions. The detailed information included can help the policymakers to take suitable preventive measures to control the global atmospheric impacts and health risk.

4.2 Processes in Power Plants

4.2.1 Conditioning and Pulverization of Coal in Power Plant

Due to limited capacity of combustion, conventional fuel firing methods (e.g., stoke firing) do not respond to fluctuations in the loads. Also, these are unsuitable for large-scale electricity generation because of difficulties in managing and removing large amounts of ash. Hence, the pulverized fuel system was adopted for large capacity power plants using lower grade fuel because of enhancement in thermal efficiency and control. Before combustion in the boiler, coal passes through different phases, which include receipt, storage, and feeding coal to boiler to release energy. In this regard, coal is first prepared for firing by pulverizing it into granular size. Raw coal is transported to a thermal power plant via different transport mechanisms and is first crushed into a smaller size by a crusher. Coal is then crushed to a fine particle form in a coal mill by application of force by hammering or by mutual effect of shearing and compressive forces. Coal from coal stock equipment is transferred to coal pulverizer (grinder) and then fed in the form of fluidized bed into a combustion chamber with the aid of hot air current.

At the power plants, large lumps of coal having a size range between 2 and 50 mm are usually available. In a thermal power plant, purpose of pulverizer is basically to crush and break down bigger coal lumps into fine particles to increase the surface area which facilitates efficient combustion of coal. For coal combustion, it is a fundamental requirement that all carbon particles get enough air to burn. Conversion into fine particle form is carried out before it is taken to boiler for combustion. If pulverization is not done, incomplete burning of coal will take place

resulting in wastage of fuel. Therefore, size of powdered coal governs the efficiency of pulverized fuel firing system. Boiler responds to load variations more promptly after pulverization. A vertical roller mill (as a grinder) is commonly used for pulverization and drying of coal. The components of mill include a bowl type plate and various rollers. Application of steady pressure is employed onto the plate with rollers and pulverization of coal is achieved by rotation of plate.

The advantage of pulverization lies in the fact that greater surface area of coal per unit mass reduces excess air required for complete combustion. Also, constant steam pressure is maintained under different load variations in pulverized coal-fired boilers through automatic control. Large variety and lower grade coals can be combusted with ease after pulverization. The requirement of furnace volume is decreased in case of pulverized boilers as the burners producing turbulence in furnace enable complete combustion with lower residence time. The unburnt carbon particles, which get emitted with ash in older combustion boilers are reduced drastically as the overall surface area gets increased.

4.2.2   Boiler

The objective of a boiler is the conversion of chemical energy of fuel into internal energy (steam) for driving turbines to generate power. A boiler includes a furnace in which fuel is burnt, surface-transmitted heat from combustion and space is utilized for steam formation and collection in a typical steam power plant (Fig. 4.2). Boiler drum receives water from boiler feed pump. In the pulverized coal furnaces, the pulverized coal from mill having, typically, 40–80 μm mass median diameter is transported into furnace with primary (carrier) air. Coal particles are then heated up to temperatures in surplus of 1500 K through conduction and radiation from hot gases (Flagan and Seinfeld 2012). Depending on ash removal technique, pulverized coal furnaces can be divided into two types: dry or wet bottom. In slag tap or wet-bottom furnaces, low or moderate ash fusion temperature coal is used. Subsequently, draining of molten ash is carried out from the bottom of the furnace. Coal with high ash fusion temperatures is fired in dry-bottom furnaces with dry ash extraction technique. Depending on the firing position of the burners, pulverized coal furnaces are classified into single (rear or front) wall, tangential, vertical, and horizontally opposed or arch fired (Davis and Buonicore 2000).

4.2.3   Fly Ash

The fine residue that is released from combustion of pulverized coal and carried from the combustion chamber by exhaust gases is referred to as fly ash. It is primarily a by-product of coal-based electric power generation plants. It is present in PM in size ranging from 0.01 to 100 μm (Davison et al. 1974). The typical
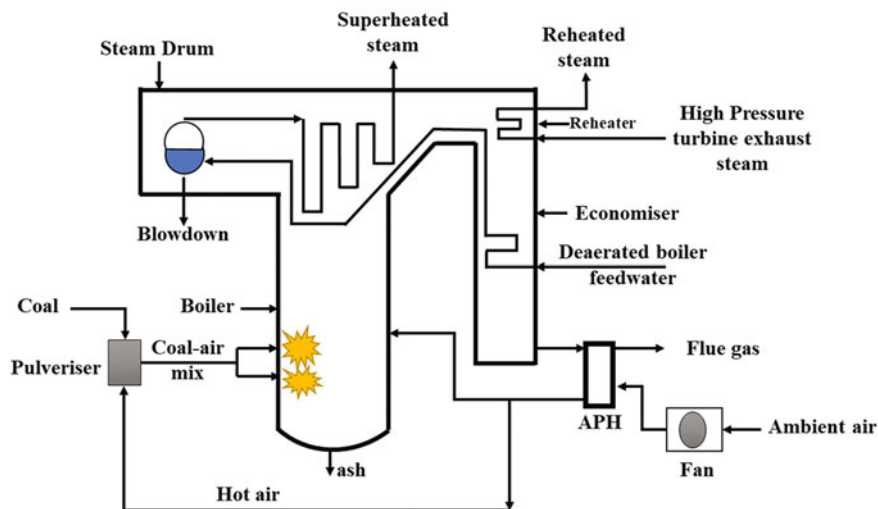
Fig. 4.2 Boiler schematic (inspired by Elshafei et al. 2014; Fan et al. 2016)

characteristics (i.e., physical, chemical, and mineralogical) depend on the category of coal, handling approaches, control devices for emission, and combustion conditions. Finely distributed components of ash reach the particle surface due to burning out of carbon matter around the mineral components.

Silica (SiO_2), magnetite (Fe_2O_3), and alumina (Al_2O_3) dominate the fly ash (Table 4.2), which also comprises of oxides, carbonates, silicates, sulfates, and hydroxides of a variety of elements which includes Mg, P, Ca, etc. Also, variable levels of heavy metals including Pb, Ba, Cu, B, As, Cd, Zn, Cr, Ni, Ag, Mo, Hg, Co, Se, and Sb are present in fly ash depending on the type of coal and conditions of combustion (Xiang et al. 2012). Previous study by Bhangare et al. (2011) reported toxic heavy metal concentrations for fly ash samples which were collected from various thermal plants having capacities varying between 90 and 3000 MW in India (Table 4.3).

Other pollutants such as polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCB) are also formed during combustion and adsorbed to fly ash. These organic pollutants are mutagenic and carcinogenic. Total PAHs and PCBs reported by a previous study in India in fly ash samples ranged from 43.6 to 936.1 ng/g and 7.3 to 178.7 ng/g, respectively, with concentration of benzo (a) pyrene which is also the most potent carcinogenic PAH, ranging from 0.8 to 18.1 ng/g (Sahu et al. 2009).

Table 4.2 Fly ash chemical composition of various coal types (Ahmaruzzaman 2010)

Components (wt%)	Lignite	Sub-bituminous	Bituminous
SiO_2	15–45	40–60	20–60
Fe_2O_3	4–15	4–10	10–40
Al_2O_3	10–25	20–30	5–35
CaO	15–40	5–30	1–12
MgO	3–10	1–6	0–5
Na_2O	0–6	0–2	0–4
SO_3	0–10	0–2	0–4
K_2O	0–4	0–4	0–3

Table 4.3 Heavy metal concentrations in fly ash samples (Bhangare et al. 2011)

Sample	Cd	Pb	Hg	As
Fly ash (μg/g)	0.6–0.93	7.6–35.3	0.51–2.13	0.19–0.35

4.2.4 Electrostatic Precipitator (ESP)

For removal of particulates from boiler-emitted flue gas, electrostatic precipitators are utilized extensively in thermal or steam power plants. It is a device that uses the induced electrostatic charge force for removal of particles flowing through a gaseous stream (e.g., air) and onto collector plates. Electrical charge is provided to particles by directing them to a corona, which is an area where flow of gaseous ions occurs (EPA/452/B-02-001). Then, electric field forces the charged particles to get deposited onto the walls. This electric field is provided from electrodes, which are maintained in the central flow lane at a very high voltage.

The power requirement of ESP is low, and it can work at high temperature and pressures due to which ESP is the preferred method for collection of small particles at a higher efficiency. ESP offers very low resistance to flow of gases through them and achieve extremely high efficiencies for removing fine particles (Mudakavi 2010). Dust particles which are deposited onto the plates are removed by shaking the plates through cams driven by external means and are collected in dust hoppers from where they are removed.

Small particles like smoke, fly ash, and mist can be effectively removed through ESP, which has a wide dust removal size range. Particles below 10 microns cannot be removed through mechanical separators or wet scrubbers (sufficient water required) but can be removed by ESP very effectively. ESP has low operation and maintenance cost and can handle large volumes of high-temperature gas. The ESPs can be configured in various ways such as (a) flat-plate precipitator, (b) plate-wire precipitator, (c) two-stage precipitator, (d) wet precipitator, and (e) tubular precipitator.

4.2.5 Sampling from Stack

Particulate concentration is derived from isokinetic sampling of a particular amount of gas from the flue gases and separation of particles from gas. Particulate matter from stationary sources is withdrawn and collected onto a filter (preferably glass fiber) (USEPA). The kinetic energy of the steam of gas in the stack should be similar to the kinetic energy of gas stream in sampling nozzle. Filter paper (thimble) is used to collect particulates down to 3 μm with stack temperature between 0 and 600 °C at particulate sampling range of 10–60 LPM. Gaseous sampling is conducted at a flow rate of 1–2 LPM on a set of impingers containing selective reagents (CPCB). Sample recovery and procedure for sampling can be adapted from central pollution control board (CPCB) or USEPA air programs chapter. For determination of particulate emissions from stationary sources, specifications of various equipment are presented in Table 4.4.

4.3 Emissions and Their Characteristics

4.3.1 Characteristics of Gaseous Emissions

Gondwana coal, which is used in the Indian subcontinent, has high ash content (35–50%), low sulfur content (0.2–0.7%), high moisture content (4–20%), and low calorific value (averaging 2500–5000 kcal/kg) (Mittal et al. 2012). Thermal power plant's operational efficiency is affected by high ash content and low calorific value resulting in enhanced emissions per kWh of produced energy. Indian power plants use ∼1.5 times higher coal amount to generate 1 kWh than that in USA (Chikkatur 2008). In India, between 2004 and 2011, the mean thermal efficiency of the coal-fired power plants was reported to be varying in the range of 32–33% (Central Electricity Authority, CEA, 2012), while a relatively high efficiency (above 35%) is attained for the power plants located in China (Seligsohn et al. 2009). Coal-fired power plant emissions contribute a major fraction in deteriorating air quality, which in turn is responsible for risks associated with human health and climate change. The estimate of emissions and their analysis lead toward implementation of pollution control regulations which includes flue gas desulfurization, constraining of emission standards for all criteria pollutants, and improved protocols for environmental impact assessments. Enormous amounts of carbon dioxide (665 million tons), sulfur dioxides (2100 ktons), nitrogen oxides (2000 ktons), carbon monoxide (1100 ktons), and volatile organic compounds (100 ktons) were emitted from various plants in India, which consumed 503 million tons of coal in 2010–2011 (Guttikunda and Jawahar 2014).

Figure 4.3 shows emission of SO_2, NO_x, CO, VOC, and CO_2 in tons per MW of power generated in various states of India. Delhi, Madhya Pradesh, Chhattisgarh, and Uttar Pradesh show the highest emission of these gases per MW of energy

Table 4.4 Specifications for the ascertainment of particulate emissions from immobile sources

S. No.	Equipment	Specifications
1	Probe nozzle	Stainless steel or glass with sharp, tapered leading edge. For isokinetic sampling range of sizes of nozzle should be available, e.g., 0.32–1.27 cm. If large volume sampling trains are utilized then the inner diameter of nozzles in increasing order of 0.16 cm should be used and calibrated
2	Probe liner	Quartz or borosilicate glass tubing. Heating system must be capable of maintaining a gas temperature of 120 ± 14 °C at the end of sampling during exit
3	Pitot tube	Type S and should be connected to probe to permit constant monitoring of velocity of stack gas
4	Differential pressure gauge	Inclined manometer or comparable device should be used
5	Filter holder	Borosilicate glass along with a silicone rubber gasket and a glass frit filter support
6	Filter heating system	A heating system which must be capable of sustaining a gas temperature of 120 ± 14 °C. Temperature in the vicinity of filter holder shall be monitored and regulated throughout sampling, and therefore temperature gauge efficient of measuring temperature to within 3 °C shall be fitted
7	Condenser	Series-connected four impingers with no leak ground glass fittings or similar non-contaminated fittings should be used
8	Metering system	Leak-free pump, vacuum gauge, the dry gas meter having a capacity of measuring volume within 2%, thermometers able to measure temperature within 3 °C shall be connected
9	Barometer	Barometer with a capacity of measuring pressure within 2.5 mm Hg

Adapted from method 5 PART 60—Standards of performance for new stationary sources, National Archives and Records Administration, Washington, DC. (USEPA 2002)

generation. However, the highest power generation units are used in Maharashtra, Gujarat, Uttar Pradesh, West Bengal, Andhra Pradesh, Chhattisgarh, and Orissa. Thus, these states contribute the maximum loading of SO_2, NO_x, CO, VOC, and CO2 to the regional air quality. At Delhi, it has been reported that 55% SO_2, 7% NO_x, 31% CO, and 13% VOC of total respective gaseous emissions arise from coal-based power plants (Guttikunda and Goel 2013). There is no legal mandatory emission standard imposed for the emission of these gases in India. SO_2 contribution to the ambient air is highest from coal-based power plant emissions as it depends on the sulfur content of coal used in these power plants. However, Indian coal's sulfur content (0.6%) is low compared to United States (1.0–1.8%) and Chinese coals (0.5–1.0%) (Guttikunda and Jawahar 2014; Reddy and Venkataraman 2002). SO_2 gases undergo physicochemical transformation to form secondary sulfates. Secondary sulfate and nitrate formation constitute about 30–40% of $PM_{2.5}$ concentration. By installation of flue gas desulfurization unit, these secondary products can be eliminated from the particulate matter loading. Thus, it
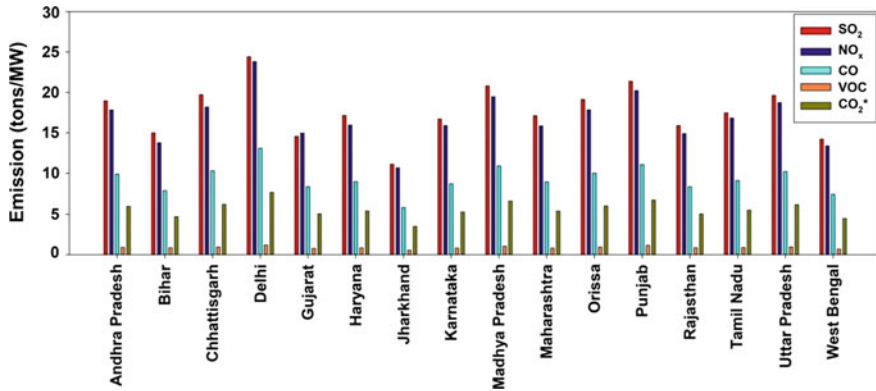
Fig. 4.3 Emission of various gases in tons/MW of power generated in different states of India. * CO_2 is generated in kilotons/MW of power generated (Guttikunda and Jawahar 2014)

has been mandated to install systems of flue gas desulfurization for the various plants operating in India, which can results in 30–40% reduction in $PM_{2.5}$ concentrations.

4.3.2 Characteristics of PM Emissions

Particulate matter composition and its concentration levels are highly dependent upon the power plant processing (combustion process and boiler operation) and properties of coal (Davis 2000). The complication in ash derived from combustion of Indian coal is the presence of high silica and alumina content since it enhances the resistivity of ash and thus decreases the removal efficiency of electrostatic precipitators (ESPs). Thus, as a preventive measure, utilization of coal with low ash content has been directed by the government for various areas according to their land use pattern. Out of 503 million tons of coal consumption in various plants (121 GW capacity) in 2010–2011, 580 ktons of particulates with a diameter less than 2.5 µm ($PM_{2.5}$) were estimated to be generated (Guttikunda and Jawahar 2014).

Figure 4.4 shows emission of particulate matter ($PM_{2.5}$ and PM_{10}) in tons/MW of power generated in different states of India. The $PM_{2.5}$ and PM_{10} levels have been observed to be highest in Delhi, Madhya Pradesh, Uttar Pradesh, and Punjab. The weighted concentration of 3.6 mg/m^3 (normalized by population) is attributed to emission from coal-fired power plants. Weighted mean of plant-wise $PM_{2.5}$ emitted from coal-based power generation units is ~ 8.1 (1.1–19.0) g/kg of coal consumed (Reddy and Venkataraman 2002). A study at Delhi reported that coal-based power plants contribute $\sim 16\%$ $PM_{2.5}$ and $\sim 15\%$ PM_{10} of the total emission of $PM_{2.5}$ and PM_{10}, respectively (Guttikunda and Goel 2013). The particle
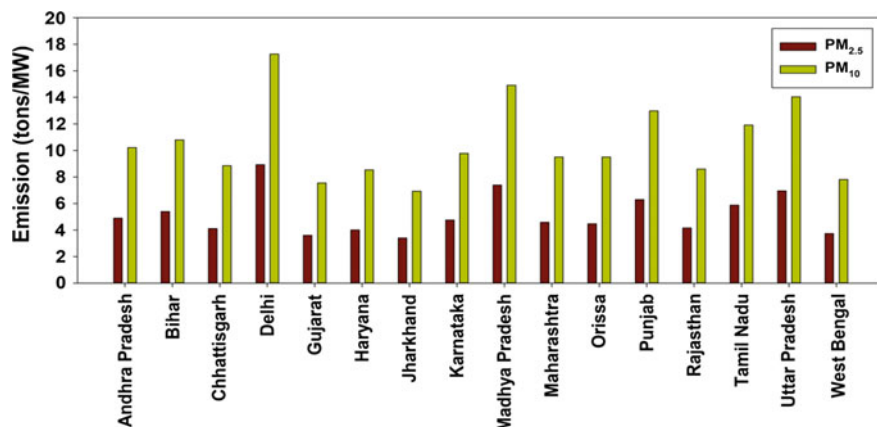
Fig. 4.4 Emission of particulate matter ($PM_{2.5}$ and PM_{10}) in tons/MW of power generated in different states of India (Guttikunda and Jawahar 2014)

size distribution is generally bimodal with one peak in the range of 0.5–0.8 μm (submicron range) and the other in 5–10 μm range (coarser) for coal-fired power plant emissions (Ehrlich et al. 2007).

The black carbon and organic matter emitted from per kg coal consumption in power plants are ∼0.077 (0.01–0.18) g and 0.33 (0.044–0.77) g (plant-wise weighted average), respectively (Reddy and Venkataraman 2002). Elevated heavy metal concentrations such as As, Pb, Cd, Cu, Hg, and Zn have been observed in particles present in flue gas (Finkelman 2007). Reddy et al. (2005) reported various chemical constituents present in bottom ash, fly ash, and flue gas from power plant located in western India and estimated Zn (1–7%), Cu (2–7%), Mn (5–8%), Co (7–10%), Cd (12–18%), Se (60–70%), Hg (70–80%), and traces of As, Fe, Pb, and Cr in the flue gas. The heavy metal concentration in the fly ash, bottom ash, flue gas, and particle associated to the gas phase is given in Table 4.5.

A study by Rey et al. (2003) suggests that Mn and U are generally found in bottom ash while Pb, As, Se, Cd, B, Sb, and Zn are concentrated in fly ash based on partitioning behavior of different elements during coal combustion. However, Hg being more volatile than other metals is generally found in the gas phase, thus coal combustion is a prominent source of mercury in the environment.

A study from Finland reports that particulate matter concentration in flue gas can be reduced by 97% by the installation of desulfurization plant (DSP) which includes baghouse filters and flue gas desulfurization unit (FGD). However, although the trace metals can be removed proficiently, input of some ionic compounds may rise in the FGD process (Saarnio et al. 2014).

In a study, where aged particles emitted from coal-fired power plants have been considered, reported that organic carbon and particulate sulfate (H_2SO_4 + neutralized sulfate) with added secondary organic aerosols form the major fraction of aged

Table 4.5 Typical concentrations of heavy metal in coal and its combustion product emitted into the environment (Reddy et al. 2005)

Elements	Fly ash (mg/kg)	Bottom ash (mg/kg)	Flue gas ($\mu g/Nm^3$)	Particle associated to gas phase ($\mu g/Nm^3$)
As	172.3	9.8	19.5	62.5
Cd	1.57	2.58	1.2	0.62
Co	0.31	0.24	0.08	0.29
Cr	13.4	10.5	0.75	1.8
Cu	328.4	389.4	6.7	16.7
Fe	54,326.5	64,325.5	16.8	230
Hg	0.29	–	22.3	0.42
Mn	4.5	3.5	0.98	3.4
Ni	73.9	69.8	3.8	1.9
Pb	266.1	325.6	1.3	0.89
Se	32.4	8.9	51.8	0.78
Zn	465	514	19	28

particles (Kang et al. 2011). In addition to this, the mass concentration is mainly dependent on SO_2/NO_x ratio, which depends on coal composition and emission controls.

Dispersal of emissions from stacks of power plant is highly subjected to the meteorological conditions as during the onset of southwest monsoons (May–September) pollutants are transported upwards toward north, whereas northeast monsoons (October–November) cause inland wider dispersion of emissions. Strong winds and higher mixing heights during spring season (March–April) lead to the upliftment of pollutants to higher altitudes in troposphere causing diminished ground concentrations. Secondary aerosol concentration (mainly sulfates and nitrates) increases during summer months due to the enhancement in photo-oxidization process. Guttikunda and Jawahar (2014) reported that secondary aerosol contribution to be between 30 and 40%, mostly in the form of aerosol sulfate (gas-particle conversion). Several researchers have compared wet and dry scavenging of such aerosol from the atmosphere (Rajeev et al. 2016, 2018).

4.4 Atmospheric and Health Impacts Due to Stack Emissions

4.4.1 Atmospheric Impacts

Large amount of gaseous and particulate emissions from coal-fired power plants has different environmental impacts associated with them. High concentration of greenhouse gases (such as CO_2) is emitted from coal-fired power plants. It had been

seen that there is an increase in the global level of CO_2 thus causing enhanced global warming and ocean acidification. Black carbon is also responsible for global warming (second after CO_2 emissions) as it absorbs the solar radiation. Black carbon concentration in the ambient PM is enhanced due to contribution from power plants as discussed in previous section. Apart from absorption properties, black carbon can be transported over long distances and mixing with other pollutants can result in the formation of atmospheric brown clouds (Ramanathan and Carmichael 2008). Coal-fired power plants are the major source of SO_2 emissions leading to elevated secondary sulfate concentrations. Increase in sulfate concentration in the atmosphere leads to increment in the acidity in precipitation which can cause acid rain. The various organic compounds emitted in the atmosphere from coal-fired power plants can be easily mixed in the presence of metals, which acts as catalyst for various chemical processes, forming compounds that can affect the radiation balance of the atmosphere, enhance cloud condensation nuclei formation and human health.

4.4.2   Health Impacts

The emissions from various thermal plants in India caused nearly 80,000–115,000 premature deaths along with 20.0 million asthma cases due to $PM_{2.5}$ exposure (Guttikunda and Jawahar 2014). The health risk of pollutants emitted from coal-based power plant, including $PM_{2.5}$, gases (O_3, NO_x, SO_2, and CO), benzene, benzo(a)pyrene, and 1,3-butadiene, includes various diseases like respiratory problems, congestive heart problem, cerebrovascular, asthma, myocardial infarction, angina pectoris, hypertension, sleep disturbance, and cancer.

The estimated total premature mortality and child mortality (under 5 years) are 80,000–115,000 and 10,000, respectively, in a year from coal-fired power plants (Guttikunda and Jawahar 2014). The other health risks like respiratory symptoms, chronic bronchitis, chest discomfort, and asthma attacks are estimated to be 625, 0.17, 8.4, and 20.9 million, respectively for 1 year. The emergency room visits and restricted activity days are estimated to be 0.9 and 160 million, respectively, for a year.

According to this data (Table 4.6), Zone 5 and 6 is the largest energy generation units, and the mortality rate is also highest in this region. However, in Kutch, the generation units have a high consumption of coal as well as emissions also but still the mortality rate is lowest. This can be attributed to the effect of coastal conditions which enables higher dispersion of pollutants, thus lowering the exposure concentrations of pollutants. The high percentage of toxic heavy metals emitted from coal-based power plants tends to increase the health risk to the exposed population. The toxic metals like Ni, Cr, Cd, and Hg are listed as a carcinogenic pollutant by US EPA. The trace amounts of these metals in the particulate matter enters the human body through either ingestion, inhalation, or even dermal contact causes different diseases. The typical concentrations of these toxic metals have been

Table 4.6 Estimated premature mortality for different regions in India (Guttikunda and Jawahar 2014)

Zone No.	Regions	Units	Installed capacity (MW)	Estimated premature mortality within the region
1.	Delhi–Haryana	8	8080	6400–8800
2.	Kutch (Gujarat)	5	9900	100–120
3.	Western Maharashtra	3	2780	1700–2400
4.	Eastern Maharashtra and Northern Andhra Pradesh	10	14,800	1100–1500
5.	Madhya Pradesh–Chhattisgarh–Jharkhand–Orissa	21	29,900	7900–11,000
6.	West Bengal–Jharkhand–Bihar	19	17,100	10,700–14,900
7.	Eastern Andhra Pradesh	2	3000	1100–1500

indicated in Table 4.5. According to some toxicological studies, transition metals present in fly ash from coal power plants (like iron) cause adverse health effects. Mercury though emitted in very less amount can cause severe health damage as it can be converted to toxic methyl mercury which can be easily deposited in terrestrial and aquatic environments. Apart from this, the large amount of volatile organic compounds (VOCs) leads to the formation of secondary organic aerosols, resulting in the production of reactive species which induces adverse health effects (Chen and Hopke 2009).

Numerous studies have reported about the toxicological effects of emissions from coal-based power plants (Ruiz et al. 2007b; Diaz et al. 2011; Godleski et al. 2011; Lemos et al. 2011 in TERESA—Toxicological Evaluation of Realistic Emissions of Source Aerosols) for assessing health impacts of coal combustion emissions. Laboratory rats have been examined to study breathing pattern and pulmonary function, blood cytology, bronchoalveolar lavage, in vivo oxidative stress, and histopathology. However, insignificant variation in the results has been observed between exposed (to the stack emission) rats and control (exposed to filtered air) ones (Rohr et al. 2011).

4.5   Estimation of Power Plant Contribution in Ambient PM

Particulate matter is classified in certain size classes such as ultrafine particles (aerodynamic diameter < 0.1 μ), $PM_{2.5}$, PM_{10}, and total suspended particulates (TSP) (Fang et al. 2003). The classification of fine and coarse particles based on size is important as they have a distinct composition, sources, formation mechanism,

temporal and spatial variability, and health effects. PM can be emitted from naturally occurring sources such as forest fires, dust storms, volcanoes and sea spray, and also from anthropogenic (human-induced) activities such as biomass burning, vehicular exhaust, industrial emissions, and land use. Out of those, chief anthropogenic combustion sources involve residential fuel for cooking and heating, industrial manufacturing plants, open biomass burning, fossil-fuel-based power plants, and vehicular engines (Gupta and Agarwal 2010). By formation mechanism, ambient PM can be divided into two categories, namely, primary and secondary aerosols. Particles which are emitted immediately into the atmosphere from natural or anthropogenic sources are called primary aerosols, whereas particles which are formed by chemical transformation of gaseous pollutants like NO_x, SO_2, NH_3, and volatile organic compounds (VOCs) are called secondary aerosols.

Receptor-based source apportionment techniques can be used to determine the sources of both primary as well as secondary aerosols. Distinct emission sources have characteristic chemical profiles of pollution which are used for the apportionment purpose. The chemical constitution of ambient PM in terms of contribution of various sources can be understood by source apportionment. Ambient samples can be amassed in the regions of interest and then analyzed for chemical composition. Source sampling can also be done to determine their chemical profile. Further, receptor modeling techniques can be utilized to ascertain the relative contributions of various sources to the ambient PM.

PM from the urban centers around the world exhibit similar major components but in distinct proportions depending on the sampling location (Harrison and Yin 2000). These major components comprise elemental carbon (EC), organic carbon (OC), sulfate (SO_4^{2-}), nitrate (NO_3^-), ammonium (NH_4^+), chloride (Cl^-), crustal materials (including metals), and biological materials (pollens, spores, bacteria, etc.). Energy production facilities such as power plants, incineration of waste, and residential combustion are the most significant stationary sources of combustion. Chemical profile data of ambient aerosols and sources such as ions, metal concentration, OC, EC, and stable isotope ratios ($\delta^{13}C$ and $\delta^{15}N$) are used for true source identification and ultimately source apportionment. The chemical profile varies from region to region and also varies according to the type of dominant sources. For example, $\delta^{13}C$ value for gaseous combustibles varies between −28.1 and −39.7‰, for liquid fuels (diesel and fuel oil) between −26.4 and −28.6‰, and for coal between −22.9 and −24.9‰ (Widory 2006). These values depend on the physical state of the samples. Combustion processes and the type of fuel burnt govern the physical and chemical characteristics of the PM released from these sources. The unique elemental profiles of various sources which contribute to airborne PM are recognized through various models. Various source apportionment models have been used widely for determining sources of ambient PM that include multiple linear regression (MLR), principal component analysis (PCA), chemical mass balance (CMB), factor analysis (FA), and positive matrix factorization (PMF). Previous PMF studies by Rajput et al. (2016) and Rai et al. (2016) apportioned the sources contributing to PM_1 at an urban location in Indo-Gangetic plain (Kanpur) and ascertained the contribution from coal combustion to be 6.5% during massive

loading. Rai et al. (2016) also employed wind speed and direction information to identify the sources of coal combustion as brick kiln cluster and a thermal power plant near the receptor site. Similar study at a wider scale can be conducted in the future to present comprehensive emission inventory due to this source.

4.6 Conclusion

This chapter discusses different processes from coal treatment in power plant to the emission by-products that elevate the atmospheric pollutant concentration in the atmosphere. Also, it presents an overview of power plant functioning and different manufacturing steps at which we can take preventive measures to control these emissions. Enormous amount of gaseous and particulate matter is being emitted from power plants which consists of high elemental carbon, sulfate, and toxic metals that have adverse impact on atmosphere as well as human health. Therefore, it is essential to estimate the contribution of power plants in ambient air pollution through advanced techniques and modeling to curb the menace of atmospheric pollutants.

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