Chapter 9
In-combustion Air Emission Control

In-combustion air emission control is accomplished by proper design and operation of a combustion device, either a burner or an engine. The existing process of in-combustion control is primarily limiting the formation of NO_x by modifying the combustion temperature and other conditions. This chapter starts with an introduction of typical combustion processes followed by specific in-combustion air emission control technologies, including low-NO_x burner, sorbent injection for in furnace SO_2 capture, and approaches to reduce soot formation, and so on.

9.1 Stationary Combustion Devices

9.1.1 Pulverized Coal/Biomass Combustion

Combustion of solid fuels takes place in a variety of stationary systems, such as home heating stove and industrial furnace. In a stove, solid fuels are burned directly without extensive size reduction. In industrial furnaces such as boilers for power generation, their sizes have to be reduced to a certain level for continuous feeding operation. This size reduction is also referred to as pulverization. A comprehensive description of pulverized coal combustion can be found in the book by Smoot and Pratt [14].

In a typical pulverized coal combustion system, coal is ground to fine particles and separated using a mesh screen before being fed to the burner. Pulverized coal particles have a mean diameter of 50 μm with the majority smaller than 200 μm by mass. Then, these coal particles are fed into the furnace by mixing with oxidants (mostly air). And combustion takes place in the flame in the open space of the furnace.

As introduced in previous chapters, ash and other pollutants are formed during solid fuel combustion. The coarse ash particles fall down to the bottom of the furnace as a solid waste, and this is referred to as bottom ash or slag, while the rest of the fine ash particles are carried along the combustion process with flue gas. In general, the

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ash particles formed in a pulverized coal combustion process is very fine and approximately 65–85 % of the ash is fly ash.

Pulverized coal combustion technology is used for the majority of fossil-fuel fired electricity generation. As to be introduced in the coming chapter, flue gas cleaning typically involves the emission controls of particulate (i.e., fly ash), oxides of sulfur and nitrogen, and others. It is characterized with high-combustion efficiency and high-combustion temperature.

9.1.2 Fluidized Bed Combustion

Advanced coal technologies have been developed to improve cost-effectiveness and environmental protection. These emerging technologies differ significantly from the existing conventional combustion technologies such as pulverized coal combustion, cyclone firing, and stoker firing. They are briefly introduced as follows.

Fluidized bed combustion (FBC) is primarily for solid fuel combustion because there is no need to fluidize liquid or gaseous fuels. In FBC, the combustion takes place in a bed where materials are fluidized by air blown from beneath of the layer of particles. The bed materials are fuel particles, sand, ash, char residue, and other solids.

There are two typical FBC systems, bubbling fluidized bed and circulating fluidized bed, which are shown in (Fig. 9.1). In bubbling fluidized bed combustion (BFBC) the bed particles behave like a boiling fluid but remain in the bed, when the gas flows upward at the velocity of 1–3 m/s. In circulating fluidized bed combustion

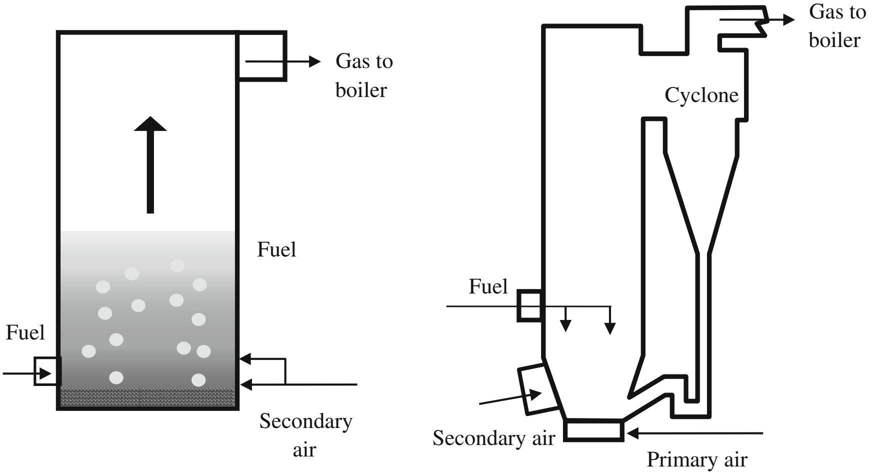


Fig. 9.1 Fluidized bed combustion chambers (*Left* Bubbling fluidized bed, *Right* Circulating fluidized bed)

(CFBC), air velocity is relatively higher than BFBC, being about 5–10 m/s at which the bed material suspension fills the entire combustion chamber.

For either case, the suspended particle size can be easily estimated from the gas speed and aerosol dynamics (Sect. 4.2). It can be determined by the balance between gravity and drag force on the particle

$$F_D = C_D\left[\frac{1}{2}\rho_g\left(V_p - V_g\right)^2\right]\left(\frac{1}{4}\pi d_p^2\right) \tag{9.1}$$

When the particle is suspended in the combustion chamber, the gravitational force equals the drag on the particle. Assuming the particle is spherical and the corresponding diameter is d_{p0}, we have

$$\frac{1}{6}\pi d_{p0}^3 g\rho_p = C_D\left[\frac{1}{2}\rho_g\left(V_p - V_g\right)^2\right]\left(\frac{1}{4}\pi d_{p0}^2\right). \tag{9.2}$$

When the fuel particle is suspended in the gas, $V_p = 0$, and the equation becomes

$$d_{p0} = \frac{3}{4}\frac{\rho_g V_g^2}{\rho_p g}C_D. \tag{9.3}$$

Fuel particles larger than this size will remain in the chamber; smaller ones will be carried away by the gas to the downstream unit. Obviously, the greater the gas speed, the larger particles can penetrate through the combustion reactor and enter downstream unit. The drag coefficient is described in Eq. (9.4).

$$C_D = \begin{cases} \frac{24}{Re_p} & Re_p \le 1 \\ \frac{Re_p}{24}\left(1 + 0.15Re_p^{0.687}\right) & 1 < Re_p \le 1000 \\ 0.44 & Re_p > 1000 \end{cases} \tag{9.4}$$

A simple form can be obtained for $Re_p \le 1$.

$$d_{p0} = \sqrt{\frac{18\mu V_g}{\rho_p g}} \tag{9.5}$$

Example 9.1: Suspended particle size in fluidized bed combustion

Consider a fluidized bed furnace in a coal fired power plant that operates at atmospheric pressure. Assume the coal particle density of 1,000 kg/m^3, and the gas temperature is about 1,100 K. The gas moves upward at a speed of 3 m/s. Use the gas properties using those of the air at the same temperature, and estiamte the suspended particle diameter.

Solution

The properties of the air at 1,100 K and 1 atm are

$\rho_p = 0.3166\ \text{kg/m}^3$, $\mu = 4.49 \times 10^{-5}\ \text{N.s/m}^2$.

If we assume $Re_p < 1$

$$d_{p0} = \sqrt{\frac{18\mu V_g}{\rho_p g}} = \sqrt{\frac{18 \times 4.49 \times 10^{-5} \times 3}{1000 \times 9.81}} = 4.97 \times 10^{-4}\,\text{m} = 0.497\,\text{mm}$$

With this size, we can calculate

$$Re_p = \frac{\rho_g V_g d_p}{\mu} = \frac{0.3166 \times 3 \times 4.97 \times 10^{-4}}{4.49 \times 10^{-5}} \gg 1$$

Therefore, our assumption of $Re_p < 1$ was invalid.

Now assume $1 < Re_p \leq 1000$ and

$$\begin{cases} d_{p0} = \frac{3}{4}\frac{\rho_g V_g^2}{\rho_p g} C_D \\ C_D = \frac{Re_p}{24}\left(1 + 0.15 Re_p^{0.687}\right) \end{cases}$$

The calculation becomes complicated, but we can solve it by iteration. Then the suspended particle size is

$$d_{p0} = 6.055\text{mm}$$

And the corresponding particle Reynolds number is $Re_p \cong 128$

Under steady operation condition, a large proportion of the bed materials leave the chamber via an exit on top of the chamber and are collected by a particle separator, most likely a cyclone for material recirculation to the bed. Cyclones are being used at temperatures of 1,000 °C in PFBC systems for solid recycling. Penetrated fine particles are called fly ash and join the flue gas. Due to the high particle concentrations in this application, particle agglomeration may occur, which favor particle separation.

The fuel particle size is larger while the furnace temperature is lower in FBC (800–950 °C) compared to pulverized coal combustion (>1,000 °C). Due to the relatively low-combustion temperature, FBC can handle low-grade fuels such as wet sludge or waste solid fuels with a relatively low-NO_x emission. The SO_x emissions can be reduced by addition of sorbent like a limestone or lime to the bed. On the other hand, the emissions of N_2O may be high.

Another drawback of CFBC is the increased fly ash, which is mainly the result of the higher velocity, smaller fuel particle size, and more intense attrition and abrasion. The fate of ash-forming material in fluidized bed is much different from that in a pulverized coal combustion chamber. Again, temperatures in CFBC are much lower and particles are larger, but mechanical stresses are stronger due to strong turbulence and the impact between particles. Although ash-forming material remains in the bed, fine particles are produced due to attrition and abrasion.

9.2 Internal Combustion Engines

An internal combustion engine is a device where atomized liquid fuels are burned to produce thermal energy (heat), which is converted to mechanical energy to drive the transportation vehicles. Combustion in engines takes place at high pressure with a variable volume, most commonly a piston for liquid fuels. The most common internal combustion engines are spark ignition engines used in automobile industry and diesel engines primarily for trucking industry. Large diesel engines are also used in off road power generation and trains. Another type of internal combustion engine is gas turbines for air craft or power generation. It is excluded from this book.

9.2.1 Spark Ignition Engines

A schematic diagram of a basic piston engine (or reciprocating engine) is shown in (Fig. 9.2). It is a metal block containing a series of chambers. The core of the engine is a cylinder that houses a piston. The inner diameter of the cylinder is also referred to as bore. The upper part of the block consists of outer walls that form hollow jackets around the cylinder walls. The hollow jackets contain the coolants to prevent the engine from being overheated. The lower part is called the crankcase, which provides rigid mounting points for the bearings to fix the crank.

The crank drives the piston up and down through the connecting rod. The angle between the crank and the centerline of the cylinder is defined as crank angle, θ. When the piston is at the top of the cylinder, it reaches its top dead center (TDC) and $\theta = 0$; when the piston is at the lowest position, bottom dead center (BDC), $\theta = \pi$. The distance between TDC and BDC is referred to as stroke.

A typical operating cycle of this type of engine involves four stokes (Fig. 9.3):

1. intake
2. compression
3. combustion/expansion
4. exhaust

When the piston moves downward, the intake camshaft opens the intake duct and fuel and air mixture is drawn into the cylinder. When the piston starts moving upward, both the intake valve and the exhaust valve are closed forming an enclosure. The rising piston compresses the air-fuel mixture. When the piston

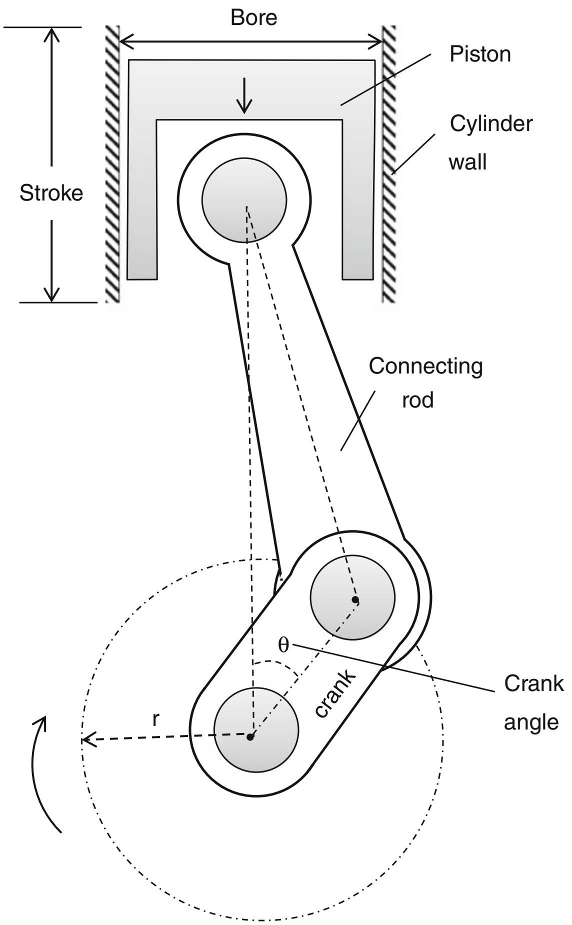


Fig. 9.2 Schematic diagram of a four-stroke piston engine

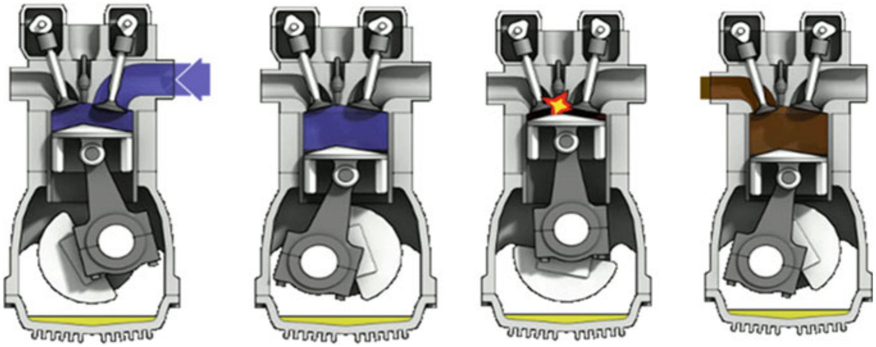


Fig. 9.3 Four-stroke piston engine cycle (Wihipedia.org)

reaches the top of the stroke, the spark plug is fired to ignite the air-fuel mixture and starts the combustion at the right instant. As the combustion proceeds, the burning mixture expands at increasing temperature and drives the piton downward to produce mechanical energy. Combustion is expected to complete when the piton reaches BDC, when the exhaust valves opens. The exhaust is pushed out of the cylinder. A new cycle starts when the rising piston reaches top of the stroke.

9.2.1.1 Carburetor

The air and fuel are premixed in the carburetor, a device that controls the flow of air and fuel. The mixture is usually at an equivalence ratio of $0.7 < \Phi < 1.4$ to match the residence time for air emission control. A cold engine is started with a fuel rich mixture to secure successful ignition. This results in highly incomplete combustion and high CO and HC emissions. Evaporation of the liquid fuel results in evaporative air emissions from the carburetor after the engine is turned off. Vapor recovery system and the adsorption-desorption system can be employed to reduce the evaporative air emissions. Activated carbon is a common adsorbent for the vapor recovery. Recycled gasoline is purged by air and the mixture is delivered to the engine for combustion without reentering the tank.

9.2.1.2 Flame in Engine

The local equivalence ratio in flame depends on the spot in the cylinder. After the ignition of the air-fuel mixture, the gas mixture is not burned instantaneously. The turbulent flame moves downward as the cylinder volume expands. The speed of the flame depends on the engine design and the operating conditions such as the equivalence ratio and the speed of the piston. As combustion continues in the cylinder, the temperature and pressure of the gas rise. This is different from the combustion in stationary systems, where pressure seems to be stable.

9.2.2 Diesel Engines

Diesel engines do not have carburetors for air-fuel premixing. Instead, air is drawn into the cylinder through the intake valve and diesel is injected into the cylinder of the engine. Diesel injection starts when it approaches the end of the compression stroke. At the moment, the high-temperature high-pressure compressed air ignites the vapor of the diesel droplets. Combustion in a diesel engine is unsteady and it varies with the fuel injection mode and mixing with the air.

In a direct injection (DI) engine, both air and fuel are turbulent and they are not homogeneously mixed. A prechamber can be used to improve the mixing effect and as a result, this type of engine is called prechamber diesel engine, or indirect injection engine (IDI). Combustion takes place in the prechamber and the burning gas enters the diesel engine cylinder through a passageway. Air emissions, especially fine particulate (soot particles) are reduced from an IDI diesel engine at the cost of lower engine efficiency.

Diesel is injected into the cylinder by multiple small nozzles. The droplets move at great initial Reynolds number because of the great relative velocity between droplets and the surrounding gas. As a result, the droplets may be further broken down to smaller ones.

Diesel engines are usually run at fuel-lean condition and the corresponding gaseous air pollutants such as CO and HC are reduced. However, the particulate matter (soot) emission is much higher than the gasoline engine because of the slower air-fuel mixing.

9.3 SO_2 Capture by Furnace Sorbent Injection

SO_2 can be captured by injection of proper sorbent such as limestone or lime into the furnace of a stationary system. The sorbent can be injected into the furnace or the hot part of the flue gas channel. This works well for older boilers with a relatively short remaining lifetime. As solid sorbent is injected into the furnace, more particles will join the fly ash and increase the load of downstream particulate control devices. Additional soot-blowing device is needed to remove solids accumulated on the inner surfaces of the furnaces, which is not a big technical problem.

9.3.1 SO_2 Capture by FSI in Pulverized Coal Combustion

The principle of furnace sorbent injection (FSI) is shown in Fig. 9.4. The concentration of SO_2 in typical flue gases from coal firing can be up to 5,000 ppmv. The efficiency of SO_2 removal by sorbent injection depends on the temperature where the sorbent is injected. When the sorbent is injected at a low-temperature area, the SO_2 removal efficiencies can be in the range of 60–75 % with Ca and S molar ratios from 2 to 4. This efficiency can be further increased at a relatively higher cost, by spraying water downstream into the flue gas duct before the particulate control devices, to reactivate the spent sorbent to capture more SO_2.

The relation between temperature and the SO_2 removal is shown in Fig. 9.5 for a sorbent such as limestone ($CaCO_3$) or hydrated lime ($Ca(OH)_2$). With other conditions the same, $Ca(OH)_2$ gives higher efficiency than $CaCO_3$.

The main solid product of the desulfurization reaction is $CaSO_4$ when temperature is below 1,200 °C. The corresponding mechanism is illustrated in Fig. 9.6. When exposed to high-temperature gases, the sorbent first decomposes to CaO, which then reacts with SO_2 and O_2 to form $CaSO_4$. A white shell of $CaSO_4$ formed by desulfurization reactions surrounds the inner unreacted CaO, which slows down

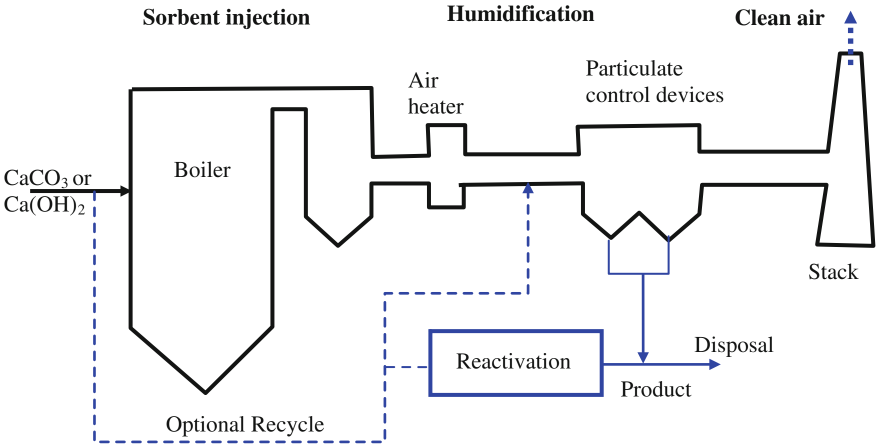
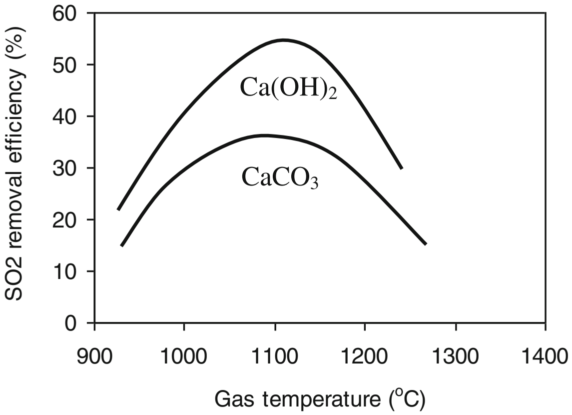


Fig. 9.4 A typical furnace sorbent injection process

Fig. 9.5 SO_2 removal efficiency by FSI



the further reaction by plugging and blocking as it is difficult for the gases to penetrate through this shell. Molar volumes of $CaCO_3$, CaO, and $CaSO_4$ are 36.9, 16.9, and 46.0 cm^3/mole, respectively; consequently, a large portion of CaO is trapped and not consumed. Trapped CaO can be released for further reaction by reactivation process.

One classic example is the Limestone Injection into the Furnace and Activation of unreacted Calcium (LIFAC) process developed by Kvaerner Pulping Power Division in Finland in the 1970s and 1980s. The desulfurization efficiencies were reported to be 65–85 % at Ca/S ratios of 2–2.5. In the LIFAC process, limestone is injected into the upper part of furnace near the superheater where it calcines into CaO:

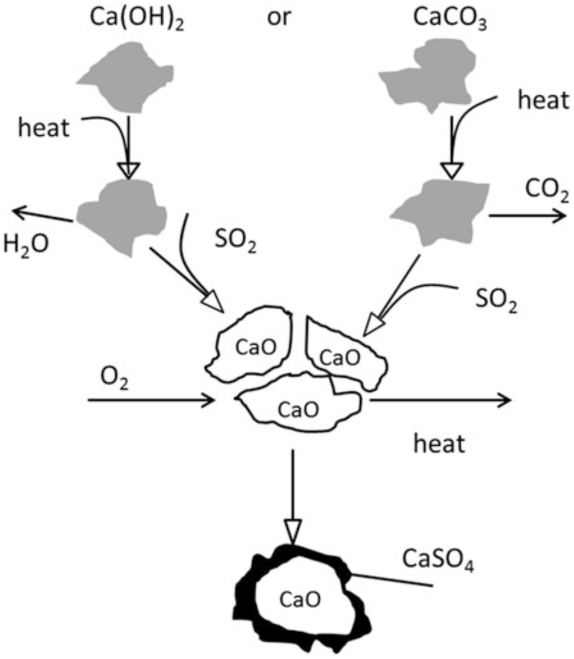


Fig. 9.6 Chemical processes during in-duct sorbent injection for SO_2 removal

$$CaCO_3 \rightarrow CaO + CO_2 \tag{9.6}$$

which then react with SO_2 and O_2 to form $CaSO_4$

$$CaO + {}^1\!/_2O_2 + SO_2 \rightarrow CaSO_4 \tag{9.7}$$

The spent sorbent is reactivated using water spray downstream in an activation reactor, where the temperature is about 400 °C.

$$CaO \ + \ H_2O \rightarrow Ca(OH)_2 \tag{9.8}$$

The newly formed calcium hydroxide ($Ca(OH)_2$), which is more reactive than CaO, reacts with more SO_2 from the flue gas stream by

$$Ca(OH)_2 + SO_2 \rightarrow CaSO_3 + H_2O \tag{9.9}$$

At low temperature the solid product is $CaSO_3$ in the flue gas duct, which is collected together with fly ash in the downstream particulate control device, an electrostatic precipitator or a filter baghouse.

9.3.2 SO_2 Capture in Fluidized Bed Combustion

As mentioned above in FBC SO_2 sorbent can be mixed with other bed materials for desulfurization, since the temperature in chamber is low, $CaSO_4$ formed remains a stable compound. In addition to relatively low-NO_x emissions due to low combustion temperature, FBC can also capture H_2S, if any, forming CaS, which can be oxidized to $CaSO_4$, before it is oxidized into SO_2.

In addition to Reactions (9.6) and (9.7), direct sulfation may also take place. Similar to fixed bed combustion, the formation of $CaSO_4$ in FBC also results in the partially used sorbent, and the reactivation of spent sorbent will give higher efficiency at lower cost of sorbent.

$$CaCO_3 + {}^1\!/\!{}_2O_2 + SO_2 \rightarrow CaSO_4 + CO_2 \tag{9.10}$$

This reaction is relatively slow because calcined limestone, CaO, is more reactive than uncalcined limestone, $CaCO_3$. In reality, the calcareous materials mined have different purity and chemical compositions, leading to large differences in SO_2 removal efficiencies, even though they are tested at identical conditions.

Desulfurization by injection of sorbent into an atmospheric FBC performs the best at 800–850 °C, which is more sensitive for BFBC than CFBC. This maximum temperature was mainly related to the stability of the $CaSO_4$. It becomes unstable at a temperature above 850 °C, when part of the desulfurization product, $CaSO_4$, react with CO and/or H_2 to produce CaS, CaO or $CaCO_3$, depending on temperature, and partial pressures of the reactants, via a complex chemistry that involves complicated step reactions [18, 21], and they are not listed herein.

The comparison among the desulfurization efficiencies in CFBC, BFBC, and pulverized coal combustion firing with FSI is shown in Fig. 9.7. It can be seen that

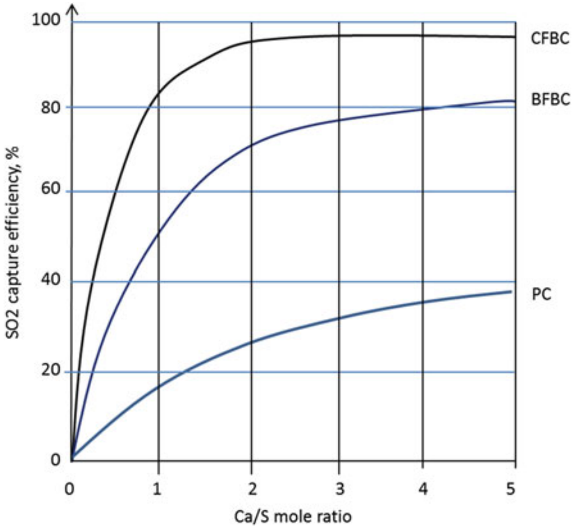


Fig. 9.7 SO_2 capture in CFBC, BFBC and PC furnaces

among the three, CFBC performs the best in terms of desulfurization efficiency while pulverized coal combustion is the worst. On the other hand, the solid residues from BFBC find limited use due to the high lime content whereas PFBC residues have better properties for concrete or cement, which is the main use of desulfurization solid residues.

9.4 In-combustion NO_x Control

Removal of nitrogen oxides during combustion process is much more favorable than post-combustion by flue gas cleaning. With the recent advances in NO_x control during the combustion stage, conditions in the boiler furnaces are no longer the same as those in the 1980s. The NO_x emissions are dramatically reduced with the development of advanced combustion techniques, such as FBC, where the combustion temperatures are low.

As introduced in combustion basics, the conversion of nitrogen in the combustion air to nitric oxide is temperature sensitive. As such, the formation of thermal NO may be reduced by lowering the combustion temperature and by minimizing the flue gas residence time. The formation rate of thermal NO appears to be practically low if the combustion temperature is below 1,400 °C, where at the temperatures above 1,600 °C, the formation of NO is strongly accelerated [22].

A variety of technologies have been developed to lower the combustion temperature. A few examples include, air staging, fuel staging, exhaust gas recirculation (EGR), reducing temperature of preheated combustion air, reducing the flame temperature by a long flame, and reducing the excess air. However, the efficiencies of the methods are case-specific, as NO_x is not the only concern. NO_x reduction is often a matter of optimization against the falling overall thermal efficiency due to the lower flame temperature and the increase of combustibles in ash and flue gas. In general, the NO reduction efficiencies of above-mentioned methods remain lower than 70 %.

9.4.1 Air Staging

NO_x formation may be substantially reduced by rearranging the combustion air supply, which is referred to as air staging [2, 10, 16]. As illustrated in Fig. 9.8, part of the air (primary air) is supplied as oxidizer at the root of the flame, where fuel rich combustion takes place and most of the HCN and NH_3 are oxidized to molecular nitrogen. The remaining air needed for combustion is supplied to the flame from the flame periphery, where little HCN or NH_3 is left to produce nitric oxide. As a result of this air staging, the peak flame temperatures in burners remain lower than the conventional burners, and the formation of thermal NO is reduced too.

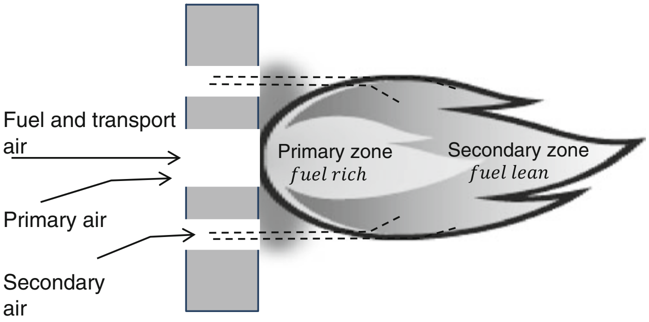


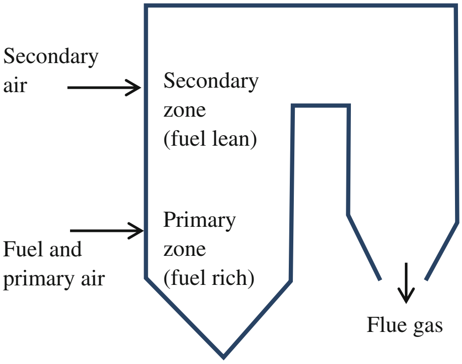
Fig. 9.8 Air staging in a burner

Air staging may also be applied to the entire furnace as shown in Fig. 9.9. The primary air is supplied at lower rows of burners, where combustion is under fuel rich condition. The secondary air or the remaining air is supplied at the upper level of the furnace, in the middle or top of the furnace. Similar principle may also be applied to grate furnaces and fluidized combustors.

While successful air staging reduces the NO_x emission, one has to carefully monitor the possible unburned air emission compounds, for example, CO, C_xH_y, and unburned carbon in ash. They are resulted from the fuel rich combustion in the primary zone.

The NO reduction by air staging varies from 10 to 50 % [22], depending on the relative quantity of volatile compounds in the fuels. For fuels with low volatiles, the fixed chars retain a considerable part of the fuel nitrogen. The nitrogen in char can form NO that cannot be effectively controlled by air staging. The share of char nitrogen in the NO emission of air-staged combustion is actually greater than that from conventional pulverized coal combustion without air staging. For pulverized coal combustion, the conversion rate of char nitrogen to NO varied from 20 to 80 %, depending primarily on the property of the coal.

Fig. 9.9 Air staging in a furnace



9.4.2 Fuel Staging

Fuel staging is also known as reburning or three-stage combustion; it utilizes fuel to reduce the formation of nitric oxide. Like the air staging technology, fuel staging may also be applied either to a low-NO_x burner or to the entire furnace [11–13]. The principles are illustrated in Fig. 9.10. In the low-NO_x burner, the same fuel is used as primary and secondary fuel. The method includes three stages, being primary, secondary stage, and final combustion.

In the primary combustion zone, the primary fuel such as coal or oil is oxidized by excess air. Both fuel NO and thermal NO are formed in this zone. Secondary fuel is usually natural gas and it is injected to the furnace at the secondary stage. It is typically corresponding to 10–20 % of the energy content of the primary fuel. At this stage, the NO formed in the primary stage is reduced to molecular nitrogen by complicated chain reactions initiated by hydrocarbon radicals (CH_i), which originate from the secondary fuel. High temperature (>1,000 °C) is favorable for these reactions, which may be written as follows.

$$NO + CH_i \rightarrow HCN + O + OH \rightarrow H_iNCO + H \rightarrow NH_i + NO \rightarrow N_2 \quad (9.11)$$

Air is added to the final combustion stage for the completion of fuel combustion. The nitrogen compounds (e.g., NO, HCN and NH_3) are oxidized back to NO and/or N_2. Different from the secondary stage, a low temperature (<1,000 °C) is preferred during the final combustion stage for the formation of molecular nitrogen. However, the temperature cannot be too low in order to minimize the formation of laughing gas (N_2O) and to maximize the oxidation of carbon monoxide. In demonstration plants the NO reduction by fuel staging could reach 30–70 % [22], with some practical problems such as increased unburned components in flue gas and increased corrosion of the furnace.

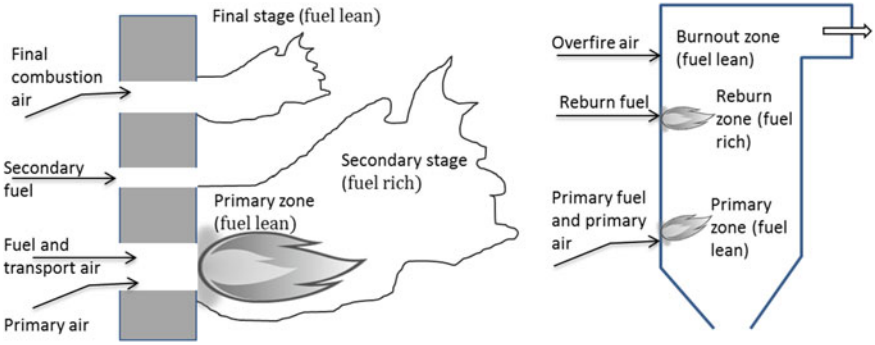


Fig. 9.10 Principle of fuel staging (*Left* low-NO_x burner, *Right* furnace)

The reduction of NO_x formation also depends on the unit size and the integration of the burners with the furnace. There are three important types of low-NO_x burners that are integrated in pulverized coal combustion processes. They are,

- wall firing,
- tangentially firing
- opposed wall firing

Each of them may be dry bottom firing and wet bottom firing, where the bottom ash is taken out in solid or liquid form, respectively. The former is preferred for high ash-content fuels. The well-known cyclone furnace is a special case of wet bottom firing furnaces [15].

9.4.3 Flue Gas Recirculation

Flue gas recirculation (FGR) is used primarily for combustion of oil or gas fuels [9]. As illustrated in Fig. 9.11, part of the flue gas is redirected to the primary combustion zone. Since the specific heat of the flue gas components, especially, H_2O, is higher than their counterparts in the furnace, FGR results in a lower temperature in the primary combustion zone and consequent low-NO_x formation.

Similar technology is being widely used for engine NO_x emission control and it is called EGR. An EGR system is effective in reduction of NO_x formation by lower combustion temperature. The main challenges are effective control system and other air pollutants due to lower temperature, such as HC and CO. Details are introduced in Sect. 9.6.

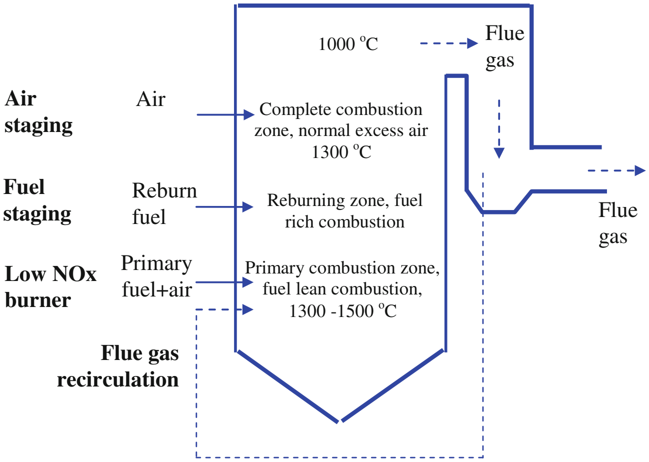


Fig. 9.11 Principles of low-NO_x formation approaches

Table 9.1 Comparison of in-furnace Low-NO_x technologies

Technology	Advantage	Disadvantage
Low excess air		Fuel burnout decreases
Low-NO_x burner (i.e., fuel staging in flame)	Always for NO_x reduction	Minor decrease in fuel burn-out
Air staging	Always for NO_x reduction	Increased risk for corrosion, slagging
Fuel staging in furnace	Always, especially when the reburn fuel is the same as the fuel in first stage	High capital cost
Flue gas recirculation	Effective for high-temperature oil or gas fired furnaces	Low efficiency

9.4.4 Combined Low-NO_x Technologies

Table 9.1 summarizes the comparison of the in-furnace low-NO_x technologies. Each of the methods has its pros and cons. In order to achieve the best NO_x reduction performance, a combination of the low-NO_x methods described above can be employed. A typical combination is illustrated in Fig. 9.11 above.

The actual selection and combination of low-NO_x combustion technologies depends on the fuel and the boiler itself. When combining several in-furnace measures for coal fired boilers, only 70 % or less of the total NO_x reduction can be achieved. The major reason for the limited NO_x reduction is that these in-combustion technologies mainly control the NO_x related to the nitrogen compounds released from the fuel at the early stage of the combustion, or in short, volatile-N.

Not all the fuel nitrogen is released during this stage, and 20–80 % may remain in the fuel forming char-*N*, which is converted to NO_x in the flue gas. The char-N content is largely unknown and varies from fuel to fuel and from furnace to furnace. Current low-NO_x methods are capable of controlling almost 100 % of the NO_x from volatile-N. Therefore, additional post-combustion NO_x control is necessary to further remove the NO_x from the flue gas before being discharged into the atmosphere.

9.5 In-combustion Soot Control

Soot formation can be reduced by controlled turbulent mixing, which promotes more complete combustion [3, 7, 8]. Additives to the fuels such as iron, nickel, manganese, or cobalt act as catalyst, can further improve the oxidation of soot, however, sometime these additives may also increase the production of soot. Feitelberg et al. [6] reported that additives of iron and manganese increased the production of soot up to a factor of 3 under all combustion conditions. They found that these additives did not affect soot particle collision rate or inception.

9.6 Engine Exhaust Gas Recirculation

The major air emissions from an engine are CO, total hydrogen carbon (HC), NO_x, and soot, which take up only 1 % of the exhaust gas. The rest are CO_2, H_2O, N_2, and O_2. The motivation of engine EGR is to further reduce these trace level emissions with minimal compensation in power and thermal efficiency.

Similar to FGR approach for stationary combustion processes, engine exhaust can also be recirculated for the reduction of NO_x emission from engines [1, 23]. With more and more stringent limits for NO_x emissions, further reductions in NO_x emissions from mobile sources without notable sacrifice to engine power have become more and more challenging. These challenges have led to recent growing R&D projects in engine EGR systems. EGR has become one of the essential techniques for engine emission reduction.

When EGR system is installed the engine intake consists of fresh air and recirculated exhaust. The percentage EGR can be defined as

$$r_{\mathrm{EGR}} = \frac{\mathrm{EGR}}{\mathrm{Air} + \mathrm{Fuel} + \mathrm{EGR}} \tag{9.12}$$

where EGR, Air and Fuel are the amount, mostly in terms of mass, of EGR, air and fuel, respectively. They can be measured in mass or volume. By mass up to 30 % of the engine exhaust can be recirculated whereas the ratio can reach 50 % by volume.

A more practical EGR ratio is based on the CO_2 concentration.

$$r_{\mathrm{EGR}} = \frac{c_{\mathrm{CO_2,in}}}{c_{\mathrm{CO_2,ex}}} \tag{9.13}$$

where $c_{\mathrm{CO_2,in}}$ is the intake CO_2 concentration and $c_{\mathrm{CO_2,ex}}$ is the exhaust CO_2 concentration.

Fresh air contains negligible amount of CO_2 compared to that in the engine exhaust. Since CO_2 is primarily a combustion product. The recycled engine exhaust carries a substantial amount of CO_2 that increases with EGR flow rate and engine loads.

CO, HC, NO_x and soot account for less than 1 % of the engine exhaust and their relative abundance depends on the engine load. The corresponding oxygen level varies from 5 % at full load to 20 % during idling. Therefore, the effectiveness of NO_x reduction by EGR also depends on engine load.

Diesel engines can operate with a high EGR ratio because the exhaust contains a high concentration of O_2 and low concentrations of CO_2 and H_2O. In addition, test results showed that cooled EGR reduces NO_x more effectively than hot EGR [20].

Unlike the exhaust from other engines with premixture aiming at certain air-fuel ratios, the relative amount of gases in a diesel exhaust depends very much on the diesel engine load. A diesel engine adjusts its fuel injection rate according to the engine load. As a result, the oxygen concentration in the diesel engine exhaust varies with the engine load. The oxygen concentration may vary from 5 to 20 %

when a diesel engine load changes from full load to idling state. And, the CO_2 concentration changes with an opposite direction. As a result, the effect in NO_x reduction by EGR depends on the diesel engine load.

9.7 Practice Problems

1. A coal having 4 % of ash content and 1.0 % of sulfur content by weight is burned by power plant at a rate of 5,000 tons/day. Calculate the amount of calcium carbonate ($CaCO_3$) needed to capture 90 % of the sulfur dioxide. Assume molar ratio Ca:S = 2.
2. A power plant burns coal at a rate of 6,000 tons/ day. The coal has 5 % of ash content and 2 % of sulfur content by weight. Calculate the amount of calcium oxide (CaO) needed to capture 100 % of the sulphur dioxide. Assume molar ratio Ca:S = 3.
3. The emission rate of NO_x from a truck is 2.5 g/km. Determine the conversion efficiency of a catalytic converter in order to meet an emission standard of 0.25 g/km.
4. In-combustion NO_x control can be achieved by air staging burner, where combustion is fuel rich in
   a. the primary zone
   b. the secondary zone
   c. both primary and secondary zones
   d. neither primary or secondary zone.
5. There are three steps in fuel staging combustion, and the combustion follows the order of
   a. fuel rich, fuel lean, fuel rich
   b. fuel lean, fuel rich, fuel lean
   c. fuel rich, fuel rich, fuel lean
   d. fuel rich, stoichiometric, fuel lean.
6. In an in-combustion SO_2 capture by lime stone injected into the furnace, the Ca: S molar ratio is 2, because
   a. 2 mol of Ca is needed in order to react with 1 mol of SO_2
   b. 2 mol of Ca is needed in order to react with 1 mol of SO_3 and 1 mol SO_2
   c. the sorbent cannot be used effectively
   d. more sorbent is needed to continue the reaction along the flue when the gas exist the furnace.

7. A practical gasoline engine emission control approach is
   a. spray finer gasoline droplets into the cylinder to reduce complete combustion products
   b. engine exhaust recirculation into air intake to reduce HC emissions
   c. optimized Stroke-Bore ratio to reduce particulate emissions
   d. fuel lean operation when the engine starts.

References and Further Readings

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