FLUE GAS DESULPHURIZATION: TECHNOLOGY FOR COAL-FIRED POWER PLANTS

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INTRODUCTION

Combustion of conventional fuels such as hard coal and brown coal, oil and natural gas cause pollution of the atmosphere with Sulphur oxides (SO_2 and SO_3), nitrogen oxides (NO_X) and dust. Discontinuing use of these energy sources in the nearest future seems unlikely. Hence, the only acceptable solution is an application of appropriate technologies and equipment eliminating substances hazardous for the environment formed from fuels or after combustion of waste gases. A decrease in the emission of Sulphur compounds to the atmosphere in the industrial scale is obtained most frequently by desulphurization of waste gases.

HISTORY

The first FGD installations in power plants were constructed in the seventies in Japan and USA, and in the eighties in Europe. Approximately 90% of all FGD installations use the wet lime/limestone method. According to the share of this desulphurization, the method is equal to 83% in the USA, 56% in Japan and 93% in Germany. In industrial conditions, especially in electric power plants, it is the only practically applied desulphurization method.

FGD SYSTEM COMPONENTS

Figure1 shows the flow diagram for a power plant boiler equipped with a typical limestone slurry system. The three main areas of interest are

(1) SO2 scrubbing module and demister.

(2) Stack gas reheater.

(3) Materials handling and sludge disposal.

SCRUBBER MODULE AND DEMISTER

The function of the scrubbing module is to absorb SO_2 from the stream of mixed combustion gases leaving the boiler. Particulate matter may be removed simultaneously or preferably by dry collection upstream of the scrubber. SO_2 is removed by contacting the gas with limestone slurry containing approximately 60% solids.

The slurry is recirculated to a holding tank where limestone is added while part of the spent solution is bled off to a settling pond feed tank. Precipitating calcium sulfate, calcium sulfite, unreacted limestone and other solids form a complicated chemical sludge which is suspended in the holding tank by agitation, then pumped to a settling pond for disposal.

The efficiency of SO_2 removal is a function of the scrubbing module design as well as gas composition and process conditions including inlet SO_2 concentration, flue gas velocity, slurry composition, liquid-to-gas ratio, and slurry pH. Although scrubber chemistry is not completely understood in detail, existing semi-empirical models can adequately predict the performance of current limestone systems.

Energy is needed in the scrubbing process to pump slurry through the scrubber circuit and to drive the fans needed to overcome gas phase pressure drops through the SO_2 absorber vessel and associated ductwork. Pumping power is a function of liquid flow and pressure drop, dependent on contractor design. Similarly, fan power requirements increase directly with the flow rate of flue gas treated and the gas phase pressure drop through the system. Both fan power and pumping power also depend on the mechanical fan or pump efficiency and the electro-mechanical efficiency of motor drives. Energy requirements are also influenced by the demister downstream of the scrubber. The purpose of this device is to remove liquid slurry entrained in the flue gas. The demister thus adds to the pressure drop incurred in the scrubber, although this is small during nominal operation. Current practice is to periodically wash the demister with clean water to remove deposits and prevent clogging. As a result, liquid droplets from the demister wash water, as well as some liquid scrubber slurry, inevitably escape the demister and remain entrained in the flue gas. Evaporation of this entrained liquid increases the energy required in reheating the gas downstream of the demister.

STACK GAS REHEATER

Reheating of the scrubbed flue gas is done to restore plume buoyancy to achieve adequate dispersion of flue gases emitted to the atmosphere. The temperature of the scrubbed gas must also be above the sulfuric acid dew point to avoid excessive corrosion of fans, reheater tubes, and ductwork. Although exit temperature requirements will depend on specific site parameters, a study reports that an 80°C exit temperature is usually sufficient for dispersion and corrosion protection. In other studies, however, exit temperatures as high as 120°C are reported.

Reheaters currently in use utilize oil firing, hot air injection, or an in-line steam heat exchanger to increase the stack gas temperature.

With oil firing, the hot combustion gases are mixed directly with the flue gas to increase the bulk temperature. This method is likely to diminish in the future in light of energy policies aimed at reducing oil and natural gas consumption.

Methods utilizing steam typically draw energy from an intermediate turbine stage of the power plant. The inline reheater accomplishes heat exchange by condensing steam in tubes directly within the flue gas stream. Alternatively, steam can be used to heat air which is then injected into the flue gas stream to achieve the desired reheat. Although this is more costly, it may be preferable where scaling or corrosion of an inline exchanger becomes excessive. The total energy requirement for gas reheat is then the sum of the input thermal energy plus the electrical power required by fans to overcome the pressure drop of the flue gas across the reheater and associated breeching.

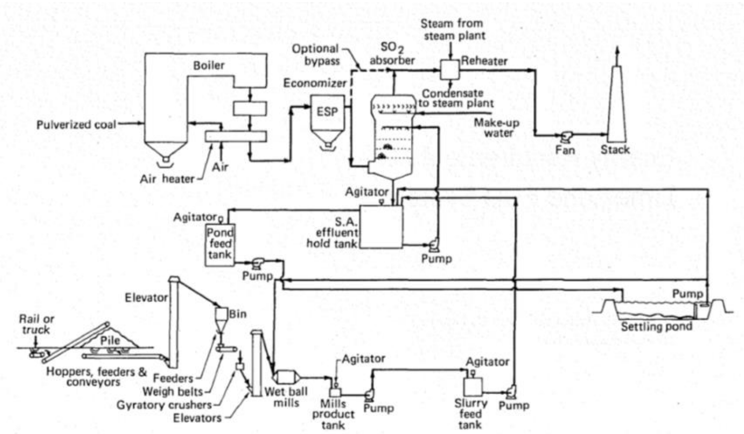

Figure1: Limestone slurry process flow diagram

RAW MATERIALS HANDLING AND SLUDGE DISPOSAL

The final area of an FGD system requiring ancillary energy is materials handling. This refers to the various stages required to process, store and feed the limestone slurry reagent, as well as equipment to handle and dispose of the waste sludge generated in the scrubber. Energy is required in the form of electricity to operate the various pumps, conveyors, and mechanical equipment needed to handle raw and waste materials.

Studies indicate that only about 10% of the total energy required by a limestone FGD system is needed for materials handling.

ENERGY OPTIMIZATION MODEL

In order to analyze FGD energy requirements systematically, a computerized model of a coal-fired steam electric power plant was developed. The model included a conventional pulverized coal-fired boiler, an electrostatic precipitator for particulate removal, a wet limestone FGD system with optional flue gas bypass, an inline steam reheater, and a separate induced draft fan for each scrubbing train.

A summary of model input parameters is shown in Table 1, along with numerical values for a "base case" plant. The size of the FGD system and a minimum number of trains were determined through a calculation of flue gas volumetric flow rate based on plant size, boiler firing characteristics, and coal composition. The model assumed complete combustion with some retention of sulfur in the boiler bottom ash. The criterion of 93.6 m^2 was used for the maximum cross-sectional area of a single scrubber module.

Sr.No.	Boiler and equipment characteristics	Base case values
1.	Gross power generation	500 MW
2.	Gross cycle heat rate	9000 Btu/kWh (9496 kJ/kWh)
3.	Boiler thermal efficiency	85.0%
4.	Percent excess air (including leakage)	33.0%
5.	Air absolute humidity	0.0044 lb H2O/lb dry air
6.	Sulfur in gas stream	95.0%
7.	Fly ash in gas stream	80.0%
8.	Electrostatic precipitator efficiency	99.5%
9.	Hot gas temperature	300°F (149°C)
10.	Coal moisture content (as fired)	9.80%
11.	Coal analysis (dry basis)	65.41%
12.	Carbon	4.70%
13.	Hydrogen	7.34%
14.	Oxygen	1.18%
15.	Nitrogen	3.50%
16.	Sulfur	
17.	Ash	17.74%
18.	Coal heating value (as fired)	10,500 Btu/lb (24,428 kJ/kg)
	Environmental regulatory constraints	
1.	Sulfur dioxide emission limit	1.2 lb/106 Btu (520 ng/J)
	Scrubber system characteristics (TCA)	
1.	Scrubbing pH	5.65
2.	Liquor Mg and Cl	0 ppm
3.	Number of beds	3
4.	Number of grids	4
5.	Heights of spheres per bed	5.0 in. (127 mm)
6.	Scrubber gas velocity	12.0 ft/sec (3.0 m/sec)
7.	Flue gas inlet temperature	300°F(149°C)
8.	Flue gas exit temperature	127°F (53°C)
9.	SO2 removal efficiency (optional)	(calculated)
10.	Water entrainment of demister	0.1% wt. of flue gas
11.	Fan efficiency	60%
12.	Pump efficiency	60%
13.	Motor efficiency	90%
	Steam reheater characteristics	
1.	Flue gas face velocity	25.0 ft/sec (7.6 m/sec)
2.	Inlet steam temperature	470°F (243°C)
3.	Heat of vaporization of steam	750 Btu/lb (1745 kJ/kg)
4.	Stack exit temperature	175°F (75°C)
5.	Outside tube diameter	1.0 in. (25.4 mm)
6.	Transverse tube spacing	1.5 in. (38.1 mm)

Table 1. Input parameters for FGD energy consumption model

TYPES OF WET SCRUBBERS USED IN FDG

To promote maximum gas-liquid surface area and residence time, a number of wet scrubber designs have been used, including spray towers, ventures, plate towers, and mobile packed beds. Because of scale build up, plugging, or erosion, which affects FGD dependability and absorber efficiency, the trend is to use simple scrubbers such as spray towers instead of more complicated ones. The configuration of the tower may be vertical or horizontal, and flue gas can flow concurrently, counter currently, or cross currently with respect to the liquid. The chief drawback of spray towers is that they require a higher liquid-to-gas ratio requirement for equivalent SO2 removal than other absorber designs.

FGD scrubbers produce a scaling wastewater that requires treatment to meet discharge regulations. However, technological advancements in ion exchange membranes and electro dialysis systems have enabled high-efficiency treatment of FGD wastewater to meet recent EPA discharge limits. The treatment approach is similar for other highly scaling industrial wastewaters.

Venturi-rod scrubbers

A venturi scrubber is a converging/diverging section of duct. The converging section accelerates the gas stream to high velocity. When the liquid stream is injected at the throat, which is the point of maximum velocity, the turbulence caused by the high gas velocity atomizes the liquid into small droplets, which creates the surface area necessary for mass transfer to take place. The higher the pressure drop in the venturi, the smaller the droplets and the higher the surface area. The penalty is in power consumption.

For simultaneous removal of SO_2 and fly ash, venturi scrubbers can be used. In fact, many of the industrial sodium-based throwaway systems are venturi scrubbers originally designed to remove particulate matter. These units were slightly modified to inject sodium-based scrubbing liquor. Although removal of both particles and SO_2 in one vessel can be economic, the problems of high-pressure drops and finding a scrubbing medium to remove heavy loadings of fly ash must be considered. However, in cases where the particle concentration is low, such as from oil-fired units, it can be more effective to remove particulate and SO_2 simultaneously.

Packed bed scrubbers

A packed scrubber consists of a tower with packing material inside. This packing material can be in the shape of saddles, rings, or some highly specialized shapes designed to maximize the contact area between the dirty gas and liquid. Packed towers typically operate at much lower pressure drops than venturi scrubbers and are therefore cheaper to operate. They also typically offer higher SO_2 removal efficiency. The drawback is that they have a greater tendency to plug up if particles are present in excess in the exhaust air stream.

Spray towers

A spray tower is the simplest type of scrubber. It consists of a tower with spray nozzles, which generate the droplets for surface contact. Spray towers are typically used when circulating a slurry. The high speed of a venturi would cause erosion problems, while a packed tower would plug up if it tried to circulate slurry.

Counter-current packed towers are infrequently used because they have a tendency to become plugged by collected particles or to scale when lime or limestone scrubbing slurries are used.

Scrubbing reagent

As explained above, alkaline sorbents are used for scrubbing flue gases to remove SO_2. Depending on the application, the two most important are lime and sodium hydroxide (also known as caustic soda). Lime is typically used on large coal- or oil-fired boilers as found in power plants, as it is very much less expensive than caustic soda. The problem is that it results in a slurry being circulated through the scrubber instead of a solution. This makes it harder on the equipment. A spray tower is typically used for this application. The use of lime results in a slurry of calcium sulphite ($CaSO_3$) that must be disposed of. Fortunately, calcium sulphite can be oxidized to produce by-product gypsum ($CaSO_4 \cdot 2H_2O$) which is marketable for use in the building products industry.

Caustic soda is limited to smaller combustion units because it is more expensive than lime, but it has the advantage that it forms a solution rather than a slurry. This makes it easier to operate. It produces a "spent caustic" solution of sodium sulphite/bisulfide (depending on the pH), or sodium sulphate that must be disposed of.

Scrubbing with sodium sulphite solution

It is possible to scrub sulphur dioxide by using a cold solution of sodium sulphite, this forms a sodium hydrogen sulphite solution. By heating this solution it is possible to reverse the reaction to form sulphur dioxide and the sodium sulphite solution. Since the sodium sulphite solution is not consumed, it is called a regenerative treatment. The application of this reaction is also known as the Wellman–Lord process.

Gas phase oxidation followed by reaction with ammonia

A new, emerging flue gas desulfurization technology has been described by the IAEA. It is a radiation technology where an intense beam of electrons is fired into the flue gas at the same time as ammonia is added to the gas. The Chendu power plant in China started up such a flue gas desulfurization unit on a 100 MW scale in 1998. The Pomorzany power plant in Poland also started up a similar sized unit in 2003 and that plant removes both sulphur and nitrogen oxides. Both plants are reported to be operating successfully. However, the accelerator design principles and manufacturing quality need further improvement for continuous operation in industrial conditions.

No radioactivity is required or created in the process. The electron beam is generated by a device similar to the electron gun in a TV set. This device is called an accelerator. This is an example of a radiation chemistry process. Where the physical effects of radiation are used to process a substance.

The action of the electron beam is to promote the oxidation of sulphur dioxide to sulphur compounds. The ammonia reacts with the sulphur compounds thus formed to produce ammonium sulphate, which can be used as a nitrogenous fertilizer. In addition, it can be used to lower the nitrogen oxide content of the flue gas. This method has attained industrial plant scale.

CHEMISTRY

SO_2 is an acid gas, and, therefore, the typical sorbent slurries or other materials used to remove the SO_2 from the flue gases are alkaline. The reaction taking place in wet scrubbing using a $CaCO_3$ (limestone) slurry produces $CaSO_3$ (calcium sulphite) and may be expressed in the simplified dry form as:

$$CaCO_{3(s)} + SO_{2(g)} \rightarrow CaSO_{3(s)} + CO_{2(g)}$$

When wet scrubbing with a $Ca(OH)_2$ (hydrated lime) slurry, the reaction also produces $CaSO_3$ (calcium sulphite) and may be expressed in the simplified dry form as:

$$Ca(OH)_{2(s)} + SO_{2(g)} \rightarrow CaSO_{3(s)} + H_2O_{(l)}$$

When wet scrubbing with a $Mg(OH)_2$ (magnesium hydroxide) slurry, the reaction produces $MgSO_3$ (magnesium sulphite) and may be expressed in the simplified dry form as:

$$Mg(OH)_{2(s)} + SO_{2(g)} \rightarrow MgSO_{3(s)} + H_2O_{(l)}$$

To partially offset the cost of the FGD installation, some designs, particularly dry sorbent injection systems, further oxidize the $CaSO_3$ (calcium sulphite) to produce marketable $CaSO_4.2H_2O$ (gypsum) that can be of high enough quality to use in wallboard and other products. The process by which this synthetic gypsum is created is also known as forced oxidation:

$$CaSO_{3(aq)} + 2H_2O_{(l)} + ½O_{2(g)} \rightarrow CaSO_4 \cdot 2H_2O_{(s)}$$

A natural alkaline usable to absorb SO_2 is seawater. The SO_2 is absorbed in the water, and when oxygen is added reacts to form sulphate ions SO_4- and free H^+. The surplus of H^+ is offset by the carbonates in seawater pushing the carbonate equilibrium to release CO_2 gas:

$$SO_{2(g)} + H_2O_{(l)} + ½O_{2(g)} \rightarrow SO_4^{2-}{}_{(aq)} + 2H^+$$

$$HCO_3^- + H^+ \rightarrow H_2O_{(l)} + CO_{2(g)}$$

In industry caustic (NaOH) is often used to scrub SO2, producing sodium sulphite:

$$2NaOH_{(aq)} + SO_{2(g)} \rightarrow Na_2SO_{3(aq)} + H_2O_{(l)}$$ [8]

NEW EMISSION STANDARDS VIDE NOTIFICATION NO. S.O. 3305(E) DATED 07.12.2015

Parameter	standards

TPPs (units) installed before 31st December 2003*	
Particulate Matter	100 mg/Nm3
Sulphur Dioxide (SO2)	600 mg/Nm3 (Units Smaller than 500MW capacity units)
	200 mg/Nm3 (for units having capacity of 500MW and above)
Oxides of Nitrogen (NOx)	Oxides of Nitrogen (NOx)
Mercury (Hg)	0.03 mg/Nm3(for units having capacity of 500MW and above)
TPPs (units) installed after 1st January 2003, up to 31st December 2016*	
Particulate Matter	50 mg/Nm3
Sulphur Dioxide (SO2)	600 mg/Nm3 (Units Smaller than 500MW capacity units)
	200 mg/Nm3 (for units having capacity of 500MW and above)
Oxides of Nitrogen (NOx)	300 mg/Nm3
Mercury (Hg)	0.03 mg/Nm3
TPPs (units) to be installed from 1st January 2017**	
Particulate Matter	30 mg/Nm3
Sulphur Dioxide (SO2)	100 mg/Nm3
Oxides of Nitrogen (NOx)	100 mg/Nm3
Mercury (Hg)	0.03 mg/Nm3

*TPPs (units) shall meet the limits within two years from the date of publication of this notification. **Includes all the TPPs (units) which have been accorded environmental clearance and are under construction".

ADVANTAGES

The wet lime/limestone method is characterized by high desulphurization effectiveness reaching 93-97%, it can be applied in the presence of large volumes of flue gas streams, changing parameters and flue gas composition and is relatively inexpensive.

Products of reaction may be reusable.

Difficulty to retrofit is moderate to low.

Inexpensive and readily available reagents.

High SO_2 removal efficiency, from 50% up to 98%.

DISADVANTAGES

High capital and O&M cost.

The Wet system generates a water waste product and may result in a visible plume.

Scaling and deposit of wet solids on absorber and downstream equipment.

Cannot be used for waste gas SO_2 concentrations greater than 2000 PPM.

Disposal of waste products significantly increases O&M cost.

The temperature of flue gases obtained from the boiler usually reaches 160°C to 180°C. In these conditions, the hazard is relatively low, as condensation of acids does not occur. If the flue gas temperature does not decrease, due to the application of thermal insulation of walls, then in the area of the entrance of flue gases to the scrubber (or pre-scrubber, depending on the construction) the application of ordinary carbon steel is possible. The situation drastically changes when the flue gas temperature decreases below the so-called acidic dew point of the respective acid, at which condensation on the installation walls occurs. First, concentrated sulphuric acid condenses, at lower temperatures hydrochloric and nitric acid. The temperature at which this occurs depends on the partial pressure of SO_3 and water vapour. In typical combustion conditions, this temperature is in the 120°C to 150°C range. The concentration of sulphuric acid in the condensate depends on the concentration of water vapor and SO_3 in the flue gas and the wall temperature.

ISSUES AND CHALLENGES – DE-SO_X

At the places where space is available, Flue Gas Desulphurization installation may take around 2 to 3 years and involve plant shutdown of 4-6 months. Dismantling / Relocation of existing plant facilities may be required in certain cases, affecting plant operation.

Disposal of gypsum in environmentally friendly manner.

Marketing avenues of gypsum. Some utilities having installed FGD are already facing problems of gypsum disposal

The Auxiliary Power Consumption shall increase for FGD operation by 1.0-1.5% affecting the plant efficiency.

The mining capacity of limestone in the country and its transportation to plants and associated challenges need to be addressed.

Quality of Indigenous Lime Stone/suitability or arrangements for its import.

ISSUES AND CHALLENGES

A limited time period for implementation for new and old plants.

Newer plants will get delayed due to the new norms.

The expected capacity may not come to the grid affecting power supply and financial hardship to stations.

The power utilities have raised their concerns and expressed their difficulties about the implementation of new environmental norms.

Two years is not sufficient for implementation in view of the time required for Design and Engineering, approvals, the arrangement of funds, tendering and erection, testing & commissioning.

The impact on power supply position due to the closure of most of the coal-based capacity due to non-fulfillment of environmental norms, as the modifications/retrofits would require long shutdowns of units.

Units operating at very low PLF of 10-20 % or have intermittent/ seasonal plant operation cannot recover the huge investment made, in their remaining lifespan without a steep rise in power tariff.

The implementation will have to be staggered for plant units to ensure power supply.

Units under advanced stage of installation, the environmental control systems would have to be considered only as retrofits.

Holding back commissioning of the units on account of environmental Standards may not be advisable as it could lead to contractual issues with equipment suppliers, the establishment of guarantees etc.

Delayed commissioning may lead to performance guarantee issues in the equipment later.

CAPEX of around ₹0.5 Cr/MW for FGD and OPEX would have to be allowed by the Regulators in tariff which ultimately would burden the consumers.

The Huge capital requirement in the next two years to make the coal-based power plants compliant with new norms.

Modification of existing PPAs to include revised tariffs.

Due to a limited supply of $DeSO_X$ systems, the excessive outflow of foreign exchange shall take place. Also, prices could increase sharply due to sudden requirements from a large number of power utilities.

As a rough estimate, the power tariff may increase by 45 to 55 paisa/kWh.

A steep rise in tariff for 15-20 years old plants, as it would not be possible to recover the investment in their remaining lifespan.

CONCLUSION

The upcoming environmental norms for thermal power plants are a welcome step in reducing emissions as well as in line with global standards. However, unlike in China, older plants, depending on their age, are grandfathered into allowing their existing emissions norms or have weaker requirements than new plants.

The technologies for complying are mostly off-the-shelf, and thus these appear technologically feasible. There is some uncertainty though about the Indian industry's capacity to meet the volumes of installation required in a short period of time.

The timeframes for compliance appear overly aggressive and somewhat unfeasible. Technical assessment and simple learning will take time, especially given limited Indian experience, but there is also a need to schedule plant shutdowns and for the tariff petitions to pass through the costs for such technologies. These could be reduced via standardized costings for pass-through to consumers (₹/kWh)

The estimated costs for compliance are measurable but likely affordable (up to few tens of paisa/kWh), translating to generate power cost increases on the order of 5-7% for plants with all equipment installed; plants without state-of-the-art upgrades would result in a lower cost increase. Translating these to end consumer average tariff increases would diminish the consumer impact substantially since not all retail electricity costs are generation (typically 70+ percent is the generation in India), and not all generation is coal, and not all coal plants need all such equipment. The economics for older plants being retrofit are more complex, with sometimes simpler and less expensive solutions sufficing, but a much shorter remaining lifespan during which to recoup the expenses.

Compliance with the norms is contingent on monitoring and enforcement, which starts with proper (and calibrated) continuous emission monitoring systems (CEMS). This extends to proper manpower to physically inspect the CEMS in statutory pollution control boards, where India lags behind China by 1-2 orders of magnitude. In addition to CEMS for power plants, there is an urgent need to increase air quality monitoring sites, especially outside the larger cities.

One needs a feasible roadmap for installation of required equipment, in addition to improvements in norms that incentivize if not mandate dispatching cleaner coal first. This requires a multi-stakeholder discussion as soon as possible, bringing together not just power plants and the government but also state utilities and grid operators.

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