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Research Article

Analytical Investigation and Design of Flue Gas Desulfurization System

Madhur Dhoot*, Vishal Shevale, Mayur Tambe, Swikruti Shelorkar, Nikhil Chougule, Krunal Meshram and MandarM. Lele

Department of Mechanical Engineering, MAEER's MITCOE, Pune 411038, Maharashtra, India

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Abstract

A wet flue gas desulfurizatio (FGD) system for boiler of capacity 300 kg/hr was investigated in this paper. It is a set of technologies used to remove sulphur dioxide from exhaust flue gases coming from fossil fuel power plants and from the emissions of other sulphur dioxide emitting processes. Sulphur dioxide is a highly noxious venom for people's health. Hence, the amount of sulphur dioxide in the emission is to be reduced before leaving it into the atmosphere to fulfill pollution norms set by government. Data on worldwide FGD applications reveal that wet FGD technologies, and specifically wet limestone FGD, have been predominantly selected over other FGD technologies because of its high desulfurization performance, relatively insoluble waste production and low operating cost. As stringent environmental regulations regarding SO_2 *emissions have been enacted in many countries, SO2 is now being removed from flue gases leaving boilers. Further future improvements in the design may possibly lead to negligible traces of sulphur dioxide in exhaust gases.*

Keywords: *Flue Gas Desulfurization, FGD sytem design,* SO_2 *removal, limestone scrubbing, flue gases*

1. Introduction

The term flue gas desulfurization has traditionally referred to wet scrubbers that remove sulphur dioxide (SO_2) emissions from large boilers (mainly coal and oil fired combustion). However, because of the requirement to control SO_2 emissions from industrial boilers and incinerators and the evolution of different types of SO_2 control systems, the terms FGD came into consideration.

FGD systems are also used to reduce SO_2 emissions from process plants such as smelters, acid plants, refineries, and pulp and paper mills. FGD systems can be categorized as dry or wet. In wet FGD scrubbing systems, the scrubbing liquid contains an alkali reagent to enhance the absorption of SO_2 and other acid gases. More than a dozen different reagents have been used, with lime and limestone being the most popular. Sodium-based solutions (sometimes referred to as clear solutions) provide better SO_2 solubility and less scaling problems than lime or limestone.

However, sodium reagents are much more expensive. Wet FGD scrubbers can further be classified as non-regenerable or regenerable. Non-regenerable processes, also called throwaway processes, produce a sludge waste that must be disposed of properly. It should be noted that in throwaway or non-regenerable processes the scrubbing liquid can still be recycled or regenerated; however, no useful product is obtained from the eventual sludge. Regenerable processes produce a product from the sludge that may be sold to partially offset the cost of operating the FGD system. Regenerated products include elemental sulfur, sulfuric acid and gypsum.

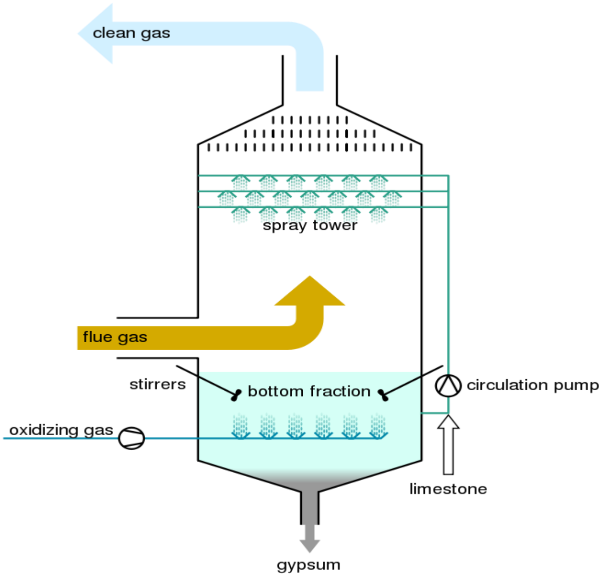

Fig.1 Working Principle of FGD system

Packing tower used in FGD systems are either vertical packed tower or horizontal packed tower. Generally

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*Corresponding author: **Madhur Dhoot**

vertical packed towers are predominantly used over horizontal packed tower.

In a vertical packed tower, the gas stream rise vertically entering near the bottom of the tower and exiting from the top of the tower. A flow of liquid containing a chemical that will absorb the desired gas constituent flows downward through the tower. To promote a large liquid surface area for good liquid-gas contact, ceramic raschig rings are generally used as packing material. A sump at the bottom of the tower collects the liquid which can be recirculated over the bed for maximum usage of the absorbing chemical. At the top of the tower, a mist eliminator removes any liquid aerosol particles to prevent them from leaving the tower.

We have developed miniature model of FGD system for boiler with following specifications:

Table 1 Specifications of boiler under investigation

Parameters	Values
Boiler Capacity	300 kg/hr steam
Fuel	Furnace Oil
Oil Temp	105°C to 115°C
Oil Flow rate (max.)	19 kg/hr
Atomizing pressure for oil	21 kg/cm^2(bars)
Flue gas flow rate (max.)	310 m^3/hr
Flue Gas Temperature	280°C

Patricia Córdoba presented a general review of the Flue Gas Desulphurization (FGD) technologies used to abate sulphur emissions from coal-fired power plants, and exposes the major physic-chemical processes occurring during wet limestone FGD(Patricia Córdoba, 2014). Another Study the use of data-driven modeling techniques, in particular artificial neural networks,is investigated to analyze the operational behavior and performance of environmental control systems at the example of a flue gas desulfurization (FGD) process(Martin Gassner *et al.*,2014). The water re-circulation favors the progressive saturation of most elements in the gypsum slurry with the subsequent increase in emission by entraining particles and droplets in the outgoing gas of FGD (Patricia Córdoba *et al.*,2012). Sulphur self-retention is more pronounced during oxyfuel combustion compared to air-firing due to the higher concentrations of SO2 and CO2. Significant reduction in SO2 emissions is obtained by limestone addition in both combustion modes(L. Al-Makhadmeh *et al.*,2015). Hot gas cleaning techniques to remove sulfur and other impurities in the flue gas streams offer the key advantages to such systems. This paper reviews briefly the Hot Gas Desulfurization (HGD) techniques and the processes' development and performance estimates, design methodology of FGD system (D. Vamvuka *et al.*,2009).

2. Research Methodology

2.1 Calculation process

For finding the dimensions of FGD unit we have followed following steps, which vary upon output of the system required. Dimensions of system are obtained based on content of SO_2 required in outlet.
We have to calculate following entities by sequence,

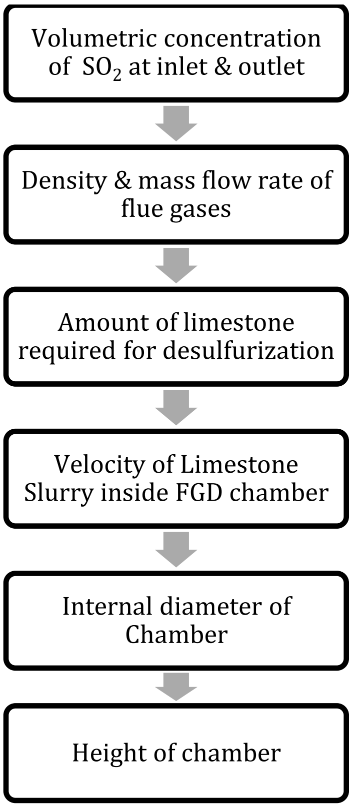

Fig.2 Design methodology for current investigation

3. Design considerations and Calculations

a)Volumetric concentration of SO_2 at inlet & outlet:

Amount of SO_2 in flue gases= 0.3% of mole per mole of flue gas

Y_{in} = Input condition of SO_2 in flue gases
$Y_{in} = 3\times10^{-3}$ moles of SO_2 / mole of air

Since, 1 mole of air (m)= 28.8×10^{-3} kg
$Y_{in} = (3\times10^{-3})/(28.8\times10^{-3}) = 0.104$ moles of SO_2/kg of air

For $\eta = 95\%$ (i.e. 95% of $SO_2$is to be removed)
Y_{out} = Output condition of SO_2 in flue gases
$Y_{out} = 0.05\ Y_{in} = 5.2\times10^{-3}$ moles of SO_2 /kg of air

b) Density and mass flow rate of flue gases:

$PV = mRT$

So, $V = \frac{RT}{P}$

where,
V = Volume of 1 mole of flue gas
T = Temperature of flue gases= 280°C= 553°K
R = Characteristic Gas Constant= 8.314
P = Flue gas Pressure = 2 bar

$$V = \frac{8.314\times 553}{2\times 1.01325\times 10^{5}} = 0.02268\ m^3$$

∴ Density ρ = m/V = 0.0288/0.02268=1.27 kg/m^3
Flue gas flow rate = 310 m^3/hr = 5.166 m^3/min
∴Mass flow rate(ṁ)= 5.166×ρ= 5.166×1.27
= 6.56 kg/min

c)Amount of limestone slurry required for desulfurization:

$$L_{min} = \frac{z}{1+c}\left[1-\frac{Yout}{Yin}\right]V$$
$$= \frac{36}{1+6}[1-0.05]6.56 = 32.05\ kg/min$$

where,
z = Multiplication factor for gas-liquid ratio required for equilibrium reaction
c = Conversion factor

But actual liquid required = 1.5to 3.0 times L_{min}
∴ L = 1.8 L_{min}= 1.8 × 32.05

L = 57.69kg/min

$$\beta = \frac{z\dot{m}}{(1+c)L} = \frac{36\times 6.56}{(1+6)57.69} = 0.5848$$

d)Number of heat transfer units (NTU):

$$NTU = \frac{ln\left(\frac{1-\eta\beta}{1-\eta}\right)}{1-\beta} = \frac{\ln\left(\frac{1-0.95\times 0.5848}{1-0.95}\right)}{1-0.5848} = 5.263$$

e)Viscosity of limestone slurry:

Now,
1 mole of $CaCO_3$=100 gm (ρ=2711 kg/m^3)
1 mole of H_2O =18 gm (ρ=1000 kg/m^3)

% of $CaCo_3$in limestone Slurry= 100/(100+18)
=84.75% by weight

∴ C_w=84.75% (i.e. concentration of solid by weight in slurry)
Specific gravity of liquid slurry= $\frac{Ss\times S}{Ss+Cw(S-Ss)}$
where,
S_s = Specific gravity of solid $CaCO_3$
S = Specific gravity of liquid H_2O
$$S_{slurry} = \frac{2.711\times 1}{2.711+0.8475(1-2.711)} = 2.15$$

Concentration of limestone in slurry by volume
∅ = 84.75x(1000/2711) = 31.25%
∅= 0.3125

∴Viscosity of slurry (μ_m)
$\mu_m=\mu_L\ [1+25\emptyset+10.05\ \emptyset^2+0.00273e^{16.6\emptyset}]$
μ_L= Viscosity of liquid i.e water = 0.89 cP
∴μ_m=2.893 cP

f) Velocity of flue gases:

$(G_x/G_y) = (L/\ \dot{m}) = 57.69/6.56 = 8.794$
where,
G_x = Liquid mass flux = L/A
G_y = Gas mass flux = V/A
ρ_y i.e Density of flue gases = 1.27 kg/m^3 = 0.079 lb/ft^3
ρ_x i.e density of slurry = 2150 kg/m^3= 135.22 lb/ft^3

$$\frac{G_X}{G_Y}\sqrt{\frac{\rho_Y}{\rho_X-\rho_Y}} = 0.2126\ \mu_m$$

From flooding curve chart, finding value against $\frac{G_X}{G_Y}\sqrt{\frac{\rho_Y}{\rho_X-\rho_Y}} = 0.2126\ \mu_m$,

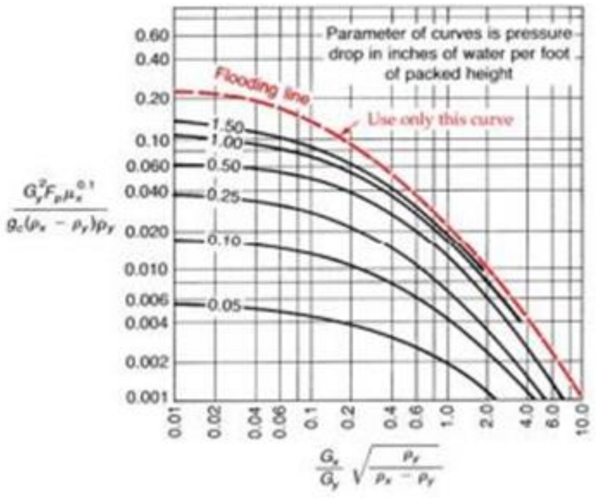

Fig.3 Flooding Curve Chart (McCabe *et al.* 1985)

$$\therefore \frac{G_Y^2\ Fp\mu_X^{0\cdot 01}}{[Gc(\rho_X-\rho_Y)\rho_Y]} = 0.082$$

where,
G_c = Gravitational constant = 32.17 $ft.lbm/s^2$
F_p = Packing Factor
For ½ inch of Raschig ring F_P = 580
μ_x= viscosity of slurry = 2.89 cP

From above equation
G_y^2 = 0.1428
$G_{y,}$= 0.378 lbm/ft^2s = 1.845 kg/m^2s
For effective operation, operate at 30% - 50% of flooding velocity consider,
G_y = 0.35 $G_{y,}$= 0.644 kg/m^3s

∴ Velocity of flue gas,
V_y = 0.644/1.27= 0.325 m/sec = 19.5 m/sec

g) Diameter and height of chamber:

Finding cross section area of chamber,

$A = \frac{\dot{m}}{\rho_Y V_Y} = \frac{6.56}{1.27 \times 19.5} = 0.265\ m^2$

As , $A = \pi D^2/4$

$0.265 = \pi D^2/4$

$D = 0.5808$ m

Taking factor of safety (FOS) into consideration
Considering, FOS = 1.5

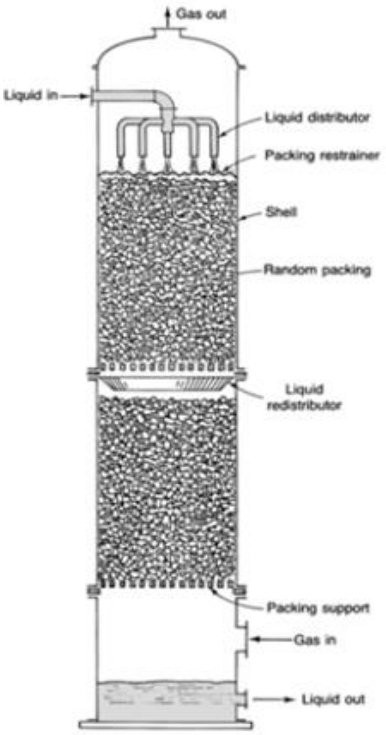

Fig.4 Chamber filled with packing material (Raschig rings)(Hongliang Gao *et al.*, 2011)

∴ Diameter of Transfer unit (chamber),

$D = 1.5 \times 0.5808$

$D = 0.871$ m

Calculating area with new diameter,

$A = \frac{\pi D^2}{4} = 0.595\ m^2$

Height of Transfer unit (chamber),

$HTU = \dot{m}/(K_a \times A)$

$= 6.56/(30 \times 0.595) = 0.3675$

where,

K_a= Overall mass transfer coefficient

Height of tower = HTU×NTU

$= 0.3675 \times 5.263$

$H = 1.93$ m

Conclusions

From the above analytical investigation and design, it can be concluded that this FGD system can be effectively used for boiler with capacity of 300 kg/hr of steam. For this particular application, it is calculated that 57.69kg/min of limestone slurry is required to absorb the SO_2emission from flue gases. The chamber with diameter of 0.871m and height of 1.92m is recommended for this flue gas desulfurization system.

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