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Absorber Sizing and Costing Required to Control SO_2 Emission from a Combustion System

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***Abstract*—This work was predicated on the design and costing of a packed column absorber required to remove SO_2 from an air/SO_2 mixture. The absorber is intended to be developed into an already existing combustion system as a retrofit. The gas flow rate basis of the computation was 40,000Kg/h. The Onda Method was used to estimate the column height as 9m and the column diameter as 2.5m while the column wall thickness as well as the domed head thickness was found to be 9mm using the BS 5500 Standard Method. In order to limit expenses, H_2O was utilized as the absorber solvent and a flow rate of 29.5Kg/s to limit solvent usage. A pressure drop of 20mmH2O/m was assumed in the design with metal pall rings of diameter 51mm and surface area of $102m^2/m^3$ chosen as the packing material. The study estimated a profound \$306,559.87 as the cost of the absorber required to remove 95% SO_2 content from the combustion waste stream.**

***Index Terms*—Absorber, Emission, Combustion, Sizing, Cost.**

I. INTRODUCTION

Reference [1] described the absorption process as the removal of undesirable gas mixtures from waste streams by the interaction of a liquid solvent in an absorber system. This process is hinged on the contact between the gas and the liquid solvent where the concentration gradient is the driving force. [2]. The mass transfer from the gas phase to the liquid phase terminates only when the two phases come to equilibrium. There will be a continual mass movement once there is a concentration difference between both media. This is the basis upon which the absorber systems operate. It utilizes the concept of gas-liquid mass movements to clean emissions from combustion systems. There are two major absorption principles used in establishing gas cleaning, the use of solubility's of the gas in the liquid solvent and neutralization of the gases by a specified solvent.

One common interest in the industry is the removal of Sulphur from combustion systems, known as Flue Gas Desulphurization (FGD). In this system, sulphur as elemental sulphur or as oxides of sulphur is removed from combustion system by the interaction of the gas stream and a liquid solvent that transfers the sulphur into the liquid stream. Reference [3] have suggested the importance of the efficiency of the FGD process as an effective process that has practicable and economic means to achieve sulphur removal. The sulphur dioxide are predominantly released during a fossil fuel combustion that has sulphur entrained in it which is predominant in coal combustion for generation of power [4]. Apart from the health hazards that these emissions cause to respiratory human systems, it also causes acid rain [5].

There are different types of absorbers, however, the packed column absorbers offer numerous requirements. These requirements include [6]:

i. It gives significant amount of surface area which necessitates maximum –interface for the gas and liquid.
ii. It helps to achieve uniform liquid distillation throughout the packing material which necessities adequate contact.
iii. It helps to also achieve uniform vapour flow throughout the cross-section of the column.

Reference [6] also reiterated the benefits of using the packed column absorbers, corrosive liquid solvents are better utilized in the packed column as this gives less maintenance cost. Packed column also handles liquid hold-up and pressure drop concerns better.

A packed column is an absorber whereby the contact between the gas and liquid streams are aided by packing materials stacked randomly or structurally to enable maximum contact with the packing materials offering higher surface area for contact. In order to effectively design a packed column adequately, procedural steps and guides are followed [6]. These steps are:

i. Choice of packing materials, selection of type al as the size of the packing
ii. Estimate the height of the column for preferred separation efficiency.
iii. Estimate the diameter of the column required to guarantee the flow rate of both the gas as well as the liquid.
iv. Selection and choice of internal features of the column.

II. DESIGN METHODS

A. Absorber Design Dimensions

Simplifying Assumptions:

i. The flue gas is assumed to be a two component gas mixture, the pollutant and air.
ii. The flue gas disposition will be assumed as an ideal gas.
iii. The solvents disposition also will be assumed to be an ideal solution.
iv. Heat changes occasioned by absorption processes will be assumed minimal.

B. Column Diameter

Flue gas flow rate, 40,000Kg/h

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Metal Pall Rings is the Packing Material with the following characteristics:
Size =51mm
Surface Area, $a, \frac{m^2}{m^3}$
Packing factor, F_P, m^{-1}
Gas density at 120^0C (Kg/m^3)
Liquid density, Kg/m^3
Liquid viscosity, Ns/m^2

$$F_{LV} = \frac{L_w^*}{V_w^*}\sqrt{\frac{\rho_V}{\rho_L}} \quad (1)$$

Where L_w^* = Liquid mass flow rate per cross sectional area, Kg/m^{2}s
V_w^* = Gas mass flow rate per unit column cross sectional area, Kg/m^{2}s
20mmH_2O/m packing is assumed as the expected pressure drop.

$$K_4 = \frac{13.1\,(V_w^*)^2 F_P \left(\frac{\mu_L}{\rho_L}\right)^{0.1}}{\rho_V\,(\rho_L - \rho_V)} \quad (2)$$

$$V_w^* = \sqrt{\frac{K_4 \rho_V (\rho_L - \rho_V)}{13.1\,F_P \left(\frac{\mu_L}{\rho_V}\right)^{0.1}}} \quad (3)$$

$$Column\ Diameter = \sqrt{\frac{4}{\pi}\,a} \quad (4)$$

Estimation of Column Height
R, bar m^3/Kmol K
Surface Tension of liquid, water, @20^0C (N/m)
Gravitational force, g (m/s^2)
Diameter of Packing, dp (m)
Surface area of packing material, a (m^2/m^3)
Effective Area, a_w [7].

$$\frac{a_w}{a} = 1 - exp\left[-1.45\left(\frac{\sigma_m}{\sigma_L}\right)^{0.75}\left(\frac{L_w^*}{a\mu_L}\right)^{0.1}\left(\frac{{L_w^*}^2}{\rho_L^2 g}\right)^{-0.05}\left(\frac{{L_w^*}^2}{\rho_L \sigma_L a}\right)^{0.2}\right] \quad (5)$$

Where:
$\sigma_m = Critical\ Surface\ tension\ for\ the\ particular\ material$
$for\ metal = \frac{75mN}{m}$
$\sigma_L = Liquid\ Surface\ tension, N/m$

For liquid phase mass coefficients [7].

$$K_L\left(\frac{\rho_L}{\mu_L g}\right)^{1/3} = 0.0051\left(\frac{L_w^*}{a_w \mu_L}\right)^{2/3}\left(\frac{\mu_L}{\rho_L D_L}\right)^{-1/2}(ad_P)^{0.4} \quad (6)$$

Where K_L = Liquid film mass transfer coefficient, m/s
d_P = Packing size, m
DL = Liquid phase diffusivity, m^2/s
For vapour phase mass transfer coefficient [7].

$$\frac{K_G RT}{aD_V} = K_5\left(\frac{V_w^*}{a\mu_V}\right)^{0.7}\left(\frac{\mu_V}{\rho_V D_V}\right)^{1/3}(ad_p)^{-2.0} \quad (7)$$

Where K_5 = 5.23 for packing sizes above 15mm
K_G = Gas film mass transfer coefficient, Kmol/m^{2}s

The film transfer unit heights is given by:

$$H_G = \frac{G_m}{K_G a_w P} \quad (8)$$

$$H_L = \frac{L_m}{K_L a_w C_t} \quad (9)$$

Where P= Column operating pressure, bar
C_t = Total concentration, Kmol/m^{3}s
G_m= Molar gas flow rate per unit cross sectional area, Kmol/m^{2}s
Lm= Molar liquid flow rate per unit cross sectional area, Kmol/m^{2}s

Column Height, Z = $H_{OG}N_{OG}$ (10)

C. Mechanical Design

1) Wall Thickness

Operating temperature of column = 120^0C however, 150^0C is used for calculations. Operating pressure is 1.013bar, however 8bar is used for estimations.
Diameter of column, D
Design stress, f
j factor = 1 (the vessel is fully welded)
From BS 5500 code equation for vessel thickness estimation, [6].

$$e = \frac{P_i D_i}{2jf - P_i} \quad (11)$$

Where P_i = Vessel pressure
D_i = Diameter of vessel
E = Vessel thickness, mm
2mm for corrosion allowance will be given. This meets BS 5500 requirement.

2) Domed Shaped Head

$$e = \frac{P_i D_i}{2jf - 0.2P_i} \quad (12)$$

2mm for corrosion allowance will be given. This meets BS 5500 requirement.

3) Cost of the Absorber

Diameter of column, Dc
Column Height, Z

$$Volume\ of\ packing = \frac{\pi D_c^2 Z}{4} \quad (13)$$

In order to estimate the cost in present times the CPI index was used:

$$Cost\ in\ 2019 = Cost\ in\ 1998 * \left[\frac{Cost\ index\ in\ 2019}{Cost\ index\ in\ 1998}\right] \quad (14)$$

Vessel cost = Bare vessel cost * Material factor *pressure factor

Cost of vessel = Vessel cost + cost of packing (15)

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III. RESULTS AND DISCUSSION

TABLE I: EMISSION RATES FROM THE INCOMPLETE COMBUSTION

GAS	EMISSION (Kg/h)
CO_2	31246
H_2O	65
NO_2	158
SO_2	20
TOTAL	31489

TABLE II: EMISSION RATES FROM THE INCOMPLETE COMBUSTION

GAS	EMISSION (Kg/h)
CO_2	9940
CO	15623
H_2O	11700
H_2S	11
NO_2	158
TOTAL	37432

The Basis of calculations is 40,000Kg/h.

From the data: Partial pressure at 1.0% w/w of SO_2 =59mmHg

Mol. Fraction in vapour = $\frac{59}{760}$

$= 0.0776$

Mol. Fraction in liquid = $\frac{\frac{1}{64}}{\frac{1}{64}+\frac{99}{18}}$

$= 0.0028$

Slope, m = $\frac{0.0776}{0.0028}$

=27.4

Assuming 1% of SO_2 in flue gas:

Partial Pressure = $\frac{1}{100}(760)$

=7.6mmHg

Assuming 95% recovery of SO_2 by the absorber: Partial pressure of SO_2 at exit will be: 7.6(0.05) = 0.38mmHg

$$\frac{y_1}{y_2} = \frac{P_1}{P_2} = \frac{7.6mmHg}{0.38mmHg} = 20$$

Reference [6] suggests that $m\frac{G_m}{L_m}$ values of between 0.6 and 0.8 as that which gives optimum values.

From material balance:

$$L_m x_1 = G_m(y_1 - y_2)$$

$$x_1 = \frac{G_m}{L_m}(0.01 * 0.95) = \frac{m}{27.4}\frac{G_m}{L_m}(0.076)$$

Inputting 0.6 and 0.8 for $x_1 = m\frac{G_m}{L_m}$ gives values with 0.8 yielding the optimal values and more liquid flow rate. Therefore, 0.8 is used.

At $m\frac{G_m}{L_m} = 0.8$, $N_{OG} = 8$

A. *Column Diameter*

Flue gas flow rate, 40,000Kg/h

Converting to Kg/s yields:

$$\frac{40{,}000}{3{,}600} = \frac{11Kg}{s} = 0.37Kmol/s$$

Liquid flow rate= $\frac{27.4}{0.8}(0.37) = \frac{12.7Kmol}{s} = 228.6Kg/s$

From the calculation, the mass flow rate of 228.6Kg/s is very high; therefore, we use 29.5Kg/s for liquid flow.

Metal Pall Rings is the Packing Material with the following characteristics:

Size =51mm

Surface Area, $a = 102\frac{m^2}{m^3}$

Packing factor, $F_P = 66m^{-1}$

Gas density at 120⁰C = $\frac{30}{22.4} * \frac{273}{393} = 0.93Kg/m^3$

Liquid density $= 1000Kg/m^3$

Liquid viscosity $= 0.001Ns/m^2$

$$F_{LV} = \frac{L_W^*}{V_W^*}\sqrt{\frac{\rho_V}{\rho_L}}$$

$$F_{LV} = \frac{29.5}{11.11}\sqrt{\frac{0.93}{1000}} = 0.08$$

From Norton Co.’s graph,

For a 20mmH_2O/m packing design for pressure drop:

$$K_4 = 0.8$$

$$K_4 = \frac{13.1\,(V_W^*)^2 F_P\left(\frac{\mu_L}{\rho_L}\right)^{0.1}}{\rho_V\,(\rho_L - \rho_V)}$$

$$V_W^* = \sqrt{\frac{K_4\rho_V(\rho_L-\rho_V)}{13.1\,F_P\left(\frac{\mu_L}{\rho_V}\right)^{0.1}}}$$

$$= \sqrt{\frac{0.8*0.93*(1000-0.93)}{13.1*66*\left(\frac{10^{-3}}{10^3}\right)^{0.1}}}$$

$$V_W^* = 1.85Kg/m^2s$$

$$Column\ Area\ Required = \frac{11.11}{1.85} = 6m^2$$

$$Column\ Diameter = \sqrt{\frac{4}{\pi}a}$$

$$Column\ Diameter = \sqrt{\frac{4}{\pi}6}$$

$$= 2.76\,m$$

2.5m however, will be used as Column diameter.

Estimation of Column Height

R= 0.08314 bar m^3/Kmol K

Surface Tension of liquid, water, @20⁰C = 70*10^{-3}N/m

Gravitational force, g = 9.81 m/s^2

Diameter of Packing, dp = 51*10^{-3}m

Surface area of packing material, a = 102m^2/m^3

Effective Area, a_w [7].

$$\frac{a_w}{a} = 1 - exp\left[-1.45\left(\frac{\sigma_m}{\sigma_L}\right)^{0.75}\left(\frac{L_W^*}{a\mu_L}\right)^{0.1}\left(\frac{L_W^{*\,2}}{\rho_L^2 g}\right)^{-0.05}\left(\frac{L_W^{*\,2}}{\rho_L\sigma_L a}\right)^{0.2}\right]$$

Where:

$\sigma_m = Critical\ Surface\ tension\ for\ the\ particular\ material\ for\ metal = \frac{75mN}{m}$

$\sigma_L = Liquid\ Surface\ tension, N/m$

$$\frac{a_w}{a} = 1 - exp\left[\begin{array}{c} -1.45\left(\frac{75*10^{-3}}{70*10^{-3}}\right)^{0.75}\left(\frac{5.9}{102*10^{-3}}\right)^{0.1} \\ \left(\frac{5.9^2*102}{1000^2*9.81}\right)^{-0.05}\left(\frac{5.9^2}{1000*70*10^{-3}*102}\right)^{0.2}\end{array}\right]$$

$$a_w = a(0.6910) = 102 * 0.6910 = 70.5\ m^2/m^3$$

For liquid phase mass coefficients [7].

$$K_L\left(\frac{\rho_L}{\mu_L g}\right)^{1/3} = 0.0051\left(\frac{L_W^*}{a_w\mu_L}\right)^{2/3}\left(\frac{\mu_L}{\rho_L D_L}\right)^{-1/2}(ad_P)^{0.4}$$

Where K_L = Liquid film mass transfer coefficient, m/s

d_P = Packing size, m

DL = Liquid phase diffusivity, m^2/s

$$K_L\left(\frac{1000}{0.001*9.81}\right)^{1/3} = 0.0051\left(\frac{5.9}{70.5*0.001}\right)^{2/3}\left(\frac{0.001}{1000*1.7*10^{-9}}\right)^{-1/2}(102*51*10^{-3})^{0.4}$$

$$46.7134K_L = 0.0051(19.1327)(0.0412)(1.9341)$$
$$K_L = 1.66*\ 10^{-4}m/s$$

For vapour phase mass transfer coefficient [7].

$$\frac{K_G RT}{aD_V} = K_5\left(\frac{V_W^*}{a\mu_V}\right)^{0.7}\left(\frac{\mu_V}{\rho_V D_V}\right)^{1/3}(ad_p)^{-2.0}$$

Where K_5 = 5.23 for packing sizes above 15mm

K_G = Gas film mass transfer coefficient, Kmol/m^{2}s

$$\frac{K_G*0.08314*393}{102*1.45*10^{-5}} = 5.23\left(\frac{2.2}{102*0.018*10^{-3}}\right)^{0.7}\left(\frac{0.018*10^{-3}}{0.93*1.45*10^{-5}}\right)^{1/3}(102*51*10^{-3})^{-2.0}$$

$$K_G = 1.38*10^{-3}Kmol/sm^2bar$$
$$G_m = \frac{2.2}{30} = 0.0733\ Kmol/sm^2$$
$$L_m = \frac{5.9}{18} = 0.3278Kmol/sm^2$$

The film transfer unit heights is given by:

$$H_G = \frac{G_m}{K_G a_w P}$$
$$H_L = \frac{L_m}{K_L a_w C_t}$$

Where P= Column operating pressure, bar

C_t = Total concentration, Kmol/m^{2}s

$$C_t = \frac{1000}{18} = 55.6Kmol/m^3$$

G_m= Molar gas flow rate per unit cross sectional area, Kmol/m^{2}s

Lm= Molar liquid flow rate per unit cross sectional area, Kmol/m^{2}s

$$H_G = \frac{0.0733}{1.38*10^{-3}*70.5*1.013} = 0.7437$$
$$H_L = \frac{0.3278}{1.66*10^{-4}*70.5*55.6} = 0.5038$$
$$H_{OG} = 0.7437 + 0.8(0.5038) = 1.14674$$

Column Height, Z = $H_{OG}N_{OG}$ =1.14674 (8) = 9m

B. Mechanical Design

1) Wall Thickness

Operating temperature of column = 120^{0}C however, 150^{0}C is used for calculations. Operating pressure is 1.013bar, however 8bar is used for estimations.

Diameter of column, D_c=2.5m = 2500mm

Design stress, f=140N/mm^2

j factor = 1 (the vessel is fully welded)

From BS 5500 code equation for vessel thickness estimation, [6].

$$e = \frac{P_i D_i}{2jf - P_i}$$

Where P_i = Vessel pressure = 8bar = 0.8N/mm^2

D_i = Diameter of vessel = 2500mm

E = Vessel thickness, mm

$$e = \frac{0.8*2500}{(2*1*140)-0.8} = \frac{2000}{279.2} = 7.16mm \approx 7mm$$

Considering 2mm for corrosion allowance gives 9mm. This meets BS 5500 requirement.

2) Domed Shaped Head

$$e = \frac{P_i D_i}{2jf - 0.2P_i}$$
$$= \frac{0.8*2500}{(2*1*140)-0.2(0.8)} = \frac{2000}{279.84} = 7.14mm \approx 7mm$$

Considering 2mm for corrosion allowance gives 9mm. This meets BS 5500 requirement.

3) Cost of the Absorber

Diameter of column = 2.50m

Column Height = 9m

$$Volume\ of\ packing = \frac{\pi D_c^2 Z}{4}$$
$$Volume\ of\ packing = \frac{2.5^2*9*\pi}{4} = 44.179m^3$$

From Table:

Cost of pall rings (stainless steel)) = \$1,360/m^3

Total cost of packing = 44.179 * \$1,360 = \$60,083.44

$$Cost\ in\ 2019 = Cost\ in\ 1998*\left[\frac{Cost\ index\ in\ 2019}{Cost\ index\ in\ 1998}\right]$$
$$= \$60{,}083.44*\left[\frac{256.143}{163.000}\right] = \$94{,}416.89$$

Bare vessel cost using height of 9m and diameter of 3m = \$45*1000 =\$45,000

Vessel cost = Bare vessel cost * Material factor *pressure factor

= \$45,000 *2*1 = \$90,000.00

Cost of vessel = Vessel cost + cost of packing

= \$90,000.00 + \$45,000.00

= \$135,000.00

$$Cost\ in\ 2019 = Cost\ in\ 1998*\left[\frac{Cost\ index\ in\ 2019}{Cost\ index\ in\ 1998}\right]$$
$$= \$135{,}000*\left[\frac{256.143}{163.000}\right] = \$212{,}142.98$$

Overall cost of the absorber =\$94,416.89 + \$212,142.98 = \$306,559.87

IV. CONCLUSION

Air pollution control is vital in order to enhance better air quality in a particular territory. Point sources emanating from combustion systems are particularly important to control because the stacks are placed such that dispersion occurs with an attendant risk to human receptors. The absorption process is a veritable method to control these emissions in power plant without control measures. Absorbers are utilized that cut down on these emissions by utilizing the absorption system. For other plants without absorber system, it is best practiced to figure out by way of sizing of the absorber to operate effectively to remove undesired emissions. A crucial parameter necessary to design the absorber include the choice of the solvent, which must be available after considering its physical characteristics. The flow rate of the solvent as well as the flow rate of the flue gas is important as this form the basis for computations another important choice is the required recovery percentage as well as absorber packing material characteristics. The other method is able to indicate the column height and diameter of the absorber. Economic consideration in terms of cost of the absorber will influence a justification for the project, therefore, it is highly imperative. Order method is highly recommended for the design and sizing of the packed column absorber however, further studies to find out more about the removal rate must be tested in a pilot plant to verify its practicability.

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