Design of a Packed Scrubber

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Abstract-*Zirconium dioxide is dried to reduce its moisture content. The wet cake of 15000kg for 24 hrs is dumped in the dryer and the fee consists of 20% Zirconium dioxide, 65% water, 10% Ammonium nitrate and 5% Ammonium sulphate. Ambient air is heated to 240 °C using a heater and is allowed to come in contact with the wet cake. The contact time for each batch is 18 hours. Moisture along with certain particles of ammonium nitrate is removed through the exhaust at 90°C. The remaining cake is collected and the composition of the dry cake of 4200kg for 24 hrs includes 70% Zirconium dioxide, 2% water, 20% Ammonium nitrate and 8% Ammonium sulphate. The inlet flow rate of ambient air for each dryer is 2800 m^3/h. design a packed scrubber for the exhaust gas.*

I. MATERIAL BALANCE

The exhaust gas is input to the packed scrubber and is scrubbed with de- mineralized water as it has highest solubility of NO_2.

BASIS: 15000kg/24hr wet cake

Tie Material: Zirconium dioxide is taken as the tie material as the amount of ZrO_2 in the wet cake and the dry cake remains same.

Feed (wet cake) stream:

Amount of ZrO_2 in wet cake = 0.2*15000 = 3000kg/24hr

Amount of H_2O in wet cake = 0.65*15000= 9750kg/24hr

Amount of NH_4NO_3 in wet cake = 0.1*15000= 1500kg/24hr

Amount of ANS in wet cake=0.05*15000=750kg/24hr

Product (dry cake) stream:

Amount of ZrO_2 in dry cake = 0.7*4200 = 2940kg/24hr

Amount of H_2O in dry cake = 0.02*4200 = 84 kg/24hr

Amount of NH_4NO_3 in dry cake = 0.2*4200 = 840 kg/24hr

Amount of ANS in dry cake = 0.08*4200 = 336kg/24hr

Exhaust stream:

Total amount of exhaust = 15000-4200 = 10800 kg/24hr

Amount of ZrO_2 in exhaust=3000-2940=60kg/24hr

Amount of H_2O in exhaust = 9750-84=9666kg/24hr

Amount of NH_4NO_3 in exhaust = 1500-840=660kg/24hr

Amount of ANS in exhaust=750-336=414kg/24hr

Total amount of exhaust=10800/24=450kg/hr

Amount of H_2O in gas stream=450/18=25kg/hr

Given flow rate for one drier = 2800kg/hr

Therefore along with gas with gas from drier =2800+25=2825kg/hr

Hence for 10 driers=2825*10=28250kg/hr

Feed to the scrubber

The exhaust from the dryer consists of ammonium nitrate along with dry air which has to be scrubbed before being let out into the atmosphere. The outlet from the dryer acts as a feed to the scrubber. Each dryer gives out 2825 kg/h and there are 10 such dryers installed. So the total feed into the scrubber consists of 28250 kg/h of gas flow. The scrubbing liquid used is water. The efficiency of the scrubber is taken as 95% as the solubility of ammonium nitrate in water is very high. The temperature is assumed to be 25^0C.

Total amount of gas in inlet = 28250 kg/h

Amount of NH_4NO_3 from 10 dryers = 660kg/24h = 27.5 kg/h

Amount of NH_4NO_3 from each dryers=27.5/10=2.75kg/hr

Molecular weight of ammonium nitrate = 80

Total amount of NH_4NO_3 entering (from 10 dryers) =27.5/80 =0.34375 kmol/h

Amount of pure gas entering = 28250-27.5= 28222.5kg/h = 28222.5/29 kmol/h = 973.18kmol/h

Reaction: $NH_4NO_3 \rightarrow NH_3 + HNO_3$

1 mole of NH_4NO_3 is equivalent to 1 mole of NO2= 1 mole of HNO_3.

Hence, moles of NO2 = 0.34375 kmol/h

Amount of HNO_3 = 46*0.343=15.81kg/h

Mole fraction of NO2 in the inlet stream = 0.34375 / (0.34375 +973.18) = 3.5×10^{-4}

Mole fraction of gas in the inlet stream= 973.18/ (0.34375 +973.18) = 0.9996

Recovery = 95%

Moles of NO2 in the outlet stream = 0.34375*0.05 = 0.0171 kmol/h

Mole fraction of NO2 in the outlet stream = (0.0171)/ (0.0171+973.18) = 1.75×10^{-5}

Assuming that the system is ideal and follows Raoult's law,

Partial pressure of HNO_3 in the feed = p1 = 3.75×10^{-4} * 760 = 0.226 mmHg

Partial pressure of HNO_3 in the exit =p2 = 1.75×10^{-5} * 760 = 0.0133 mmHg

From the paper published by Idaho National Engineering laboratory titled Physical property parameter set for modeling ICPP aqueous wastes with ASPEN electrolyte NRTL model , the equilibrium curve data for the vapor liquid equilibrium of HNO_3 and H_2O system at 760 torr and 25^0C is depicted in the graph below.

The slope of the equilibrium curve is hence found out as follows.

Slope = m= (y_2-y_1) / (x_2-x_1) = (log (0.1)-log (0.01))/ (0.26-0.11) = 6.66

II. DETERMINATION OF NUMBER OF STAGES

Performing mass balance around the scrubber at the inlet and outlet, we get,

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

Where,

L_m= Liquid flow rate in inlet in kmol/s

G_m= Gas flow rate in inlet in kmol/s

x_1 = Moles of HNO_3 in the outlet liquid stream

y_1 = moles of HNO_3 in the inlet gas stream = Partial pressure of HNO_3 in inlet gas stream =0.226 mmHg

y_2 = moles of HNO_3 in the outlet gas stream = Partial pressure of HNO_3 in outlet gas stream = 0.0133 mmHg

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

$x_1=$ $(G_m/L_m)*(y_1-y_2)*(\%Recovery)$ = $(G_m/L_m)*(0.226-0.0133)*0.95$

= $(G_m/L_m)*0.2020$

$x_1=$ $(m*G_m/L_m)*(0.2020/m)$ = $(m*G_m/L_m)*(0.2020/6.66) = (m*G_m/L_m)*0.0306$

Our aim here is to determine the flow rate of water such that it accounts for maximum separation in an economical way. From Coulson and Richardson volume 6, figure 11.40, a graph is plotted for approximate number of stages v/s $(m*G_m/L_m)$.

To determine the number of stages at different flow rates, an optimization is done based on the graph below as follows.

$y_1/y_2= p_1/p_2= 0.226/0.0133 = 17$

$(m*G_m/L_m)$	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
N_{OG}	3.8	4.1	4.5	5.1	5.8	7.2	9.5	14

From the graph it is evident that for the selection of optimum number of stages the value of $(m*G_m/L_m)$ should be around 0.4 and 0.7. If smaller values of $(m*G_m/L_m)$ are chosen, then for a small change in number of stages requires a large variation in the liquid flow rate. Similarly, if $((m*G_m/L_m)$ is chosen above 0.7, then for a small decrease in liquid rate, the increase in the number of stages is very high.

At $(m*G_m/L_m)$ = 0.4, x1= 0.0303*0.4 = 0.0121

At $(m*G_m/L_m)$ = 0.7, x1= 0.0303*0.7= 0.0212

Among the two, a higher value of x_1 is given by $(m*G_m/L_m) = 0.7$. Hence we consider the number of stages to be equal to 5-8. Since the number of stages cannot be a decimal, we can either approximate it to 5 or 6.Considering N_{OG} as 5 for calculations.

III.   ESTIMATION OF COLUMN DIAMETER

Gas flow rate into the scrubber = G= 28250kg/h = 7.8470 kg/s = 0.27 kmol/s

Liquid flow rate = L = $(m*G)/0.6$ = $(6.66*0.270)/0.7$ = 2.578 kmol/s = 46.34kg/s

Gas flow rate in kg/s = $G* = 7.842$ kg/s

Liquid flow rate in kg/s = $L* = 46.34$kg/s

Gas density at 25^0C =ρ_v = $(29/22.4)*(273/298)$ = 1.186 kg/m^3

Liquid density = Density of water = $\rho_L = 1000$ kg/m^3

Liquid viscosity = Viscosity of water= $\mu_L = 0.001$ Ns/m^2

Gas viscosity = $\mu_v = 1.98*10^{-5}$ Ns/m^2

A factor known as K_4 is found which correlates the liquid and gas flow rates, physical properties of the system and packing characteristics, F_{LV}, with the gas mass flow rate per unit cross sectional area for a constant pressure drop system.

$F_{LV} = (L_w*/G_w*)*(\rho_v/\rho_L)^{0.5}$ = $(46.34/7.847)*(1.186/1000)^{0.5}$ = 0.203

From the graph, figure 11.44, Coulson and Richardson volume 6, k_4 for F_{LV} =0.203 is found to be

K_4 at flooding = 0.65

K_4 at pressure drop 21 mm of water/meter of packed bed = 0.8

Percentage flooding = (K_4 / K_4 at flooding) *100 = $(0.65/0.8)^{0.5}*100$ = 80.25 %

Gas mass flow rate per unit column cross sectional area, V_w*, is found in kg/m^2 s.

$V_w* = (K_4*\rho_v*(\rho_L-\rho_v))/(13.1*F_p*(\mu_L/\rho_L)^{0.1}))^{0.5}$

F_p = Packing factor

The material chosen for packing is ceramic intalox saddles of 38mm diameter whose packing factor is 170.

$V_w* = 1.17$ kg/m^2 s

Column required = (Actual gas flow rate)/ (Gas mass flow rate per unit column cross sectional area)

$= (7.847/1.17) = 6.684$ m^2

Diameter of column = $((4*column\ area)/\pi)^{0.5}$ = 2.9 m

Actual column area = $(\pi *diameter^2)/4$ = 7.064 m^2

Column diameter to packing size ratio = diameter/size of packing = 2.9 m/38 mm = 76.94

Percentage flooding at the given diameter = 80.25*(Column required/Actual column area) = 76.87%

IV.   ESTIMATION OF COLUMN HEIGHT

Cornell's Method

The Cornell's method is helpful for developing the heights of liquid and gas phase transfer units based on an empirical correlation which takes into account the physical properties of the system along with the liquid and gas mass flow rates. Several factors are to be calculated from the equations or from the corresponding points from the graph and these depend on the value of percentage flooding.

The graphs referred are figure 11.41, 11.42, and 11.43, Coulson and Richardson volume 6.

Where: H_G = height of a gas-phase transfer unit, m,

H_G=height of a liquid-phase transfer unit, m,

Sc_v= gas Schmidt number = $(\mu_v/\rho_v D_v)$,

Sc_L= liquid Schmidt number = $(\mu_L/\rho_L D_L)$,

D_c = column diameter, m,

Z =column height, m,

K_3 =percentage flooding correction factor, from Figure 11.41,

Ψ_h =H_G factor from Figure 11.42,

ϕ_h=HL factor from Figure 11.43,

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$L*_w$= liquid mass flow-rate per unit area column cross-sectional area, kg/m^2s,

f_1=liquid viscosity correction factor = $(\mu_v/\mu_w)^{0.16}$

f_2=liquid density correction factor = $(\rho_w/\rho_v)^{1.25}$

f_3 = surface tension correction factor = $(\sigma_w/\sigma_L)^{0.8}$

At percentage flooding = 77%,

K_3 = 0.6

Ψ_h = 80

D_c = column diameter = 2.9m

Z= column height (predicted) =15m

D_L = diffusivity of liquid = diffusivity of water = $1.64 * 10^{-9} m^2/s$

D_v = diffusivity of vapor = diffusivity of air = $22.07 * 10^{-6} m^2/s$

Sc_v= gas Schmidt number = $(\mu_v/\rho_v D_v)$,

Sc_L= liquid Schmidt number = $(\mu_L/\rho_L D_L)$,

L_w*= liquid mass flow rate per unit column cross sectional area = $L*/$column area = 46.34/6.68 = $6.93 kg/m^2 s$

At L_w*=46.34 kg/s, Φ_h = correlation parameter = 0.065

Height of gas phase transfer unit =H_G

f_1=liquid viscosity correction factor = $(\mu_v/\mu_w)^{0.16}$=1

f_2=liquid density correction factor = $(\rho_w/\rho_v)^{1.25}$=1

f_3 = surface tension correction factor = $(\sigma_w/\sigma_L)^{0.8}$=1

H_G= $(0.011*\Psi_h *Sc_v^{0.5}*(D_c/0.305)^{1.11}*(Z/3.05)^{0.33})/$ $((L_w*)*f_1*f_2*f_3)$ = 3.24 m

Height of liquid phase transfer unit = H_L

H_L=$0.305*\Phi_h*Sc_L^{0.5}*K_3*(Z/3.05)^{0.15}$ = 0.35

Total height of the column = H_{OG} = H_G + $H_L*m(G_m/L_m)$ = 3.46 m

Z= $N_{OG}*H_{OG}$=5*3.46=17.34m

The total height of packing's in the column is 4.74 m which approximates to 5m. Hence the assumption made in the beginning of the calculations is right.

Onda's Method:

Onda et al. (1968) published useful correlations for the film mass-transfer coefficients k_G and k_L and the effective wetted area of the packing a_w, which can be used to calculate H_G and H_L.

The equation for the effective area is:

$$\frac{a_w}{a}=1-exp[-1.45 (\frac{\sigma_c}{\sigma_L})^{0.75} (L_w*/a\mu_L)^{0.1} (L_w*^2 a/\rho^2_L g)^{-0.05} ((L_w*^2/\rho_L \sigma_L a)^{0.2}]$$

L_w*=liquid mass flow rate per unit cross-section area kg/m^2s =$6.93 kg/m^2s$,

a_w = effective interfacial area of packing per unit volume, m^2/m^3,

a= actual area of packing per unit volume (see table 11.3), m^2/m^3 =$194 m^2/m^3$,

d_p= packing size, m =$38*10^{-3}$m,

σ_c = critical surface tension for the particular packing material = $61 *10^{-3}$N/m,

σ_L = liquid surface tension ,N/m =$72*10^{-3}$N/m,

μ_L= 10^{-3}kg/ms,

ρ_L= $1000^3 kg/m^3$,

g=$9.81 m^2/s$,

Therefore **a_w=109.72m^2/m^3**. And the mass coefficients:

$$k_L(\rho_L/\mu_L g)^{1/3}=0.0051(L_w*/a\mu_L)^{2/3} (\mu_L/\rho_L D_L)^{-1/2} (ad_p)^{0.4}$$

k_L=liquid film mass transfer coefficient, $kmol/m^2s(kmol/m^3)$=m/s.

μ_L=10^{-3}kg/ms,

ρ_L= $1000^3 kg/m^3$,

g=$9.81 m^2/s$,

D_L = diffusivity of liquid = diffusivity of water = $1.64 * 10^{-9} m^2/s$,

L_w*=liquid mass flow rate per unit cross-section area kg/m^2s =$6.93 kg/m^2s$,

a=actual area of packing per unit volume (see table 11.3), m^2/m^3 =$194 m^2/m^3$,

d_p= packing size, m =$38*10^{-3}$m,

Therefore

k_L= $1.55*10^{-4}$m/s.

$$(k_G RT/aD_v)= K_5 (V_w*/a\mu_v)^{0.7}(\mu_v/\rho_v D_v)^{1/3} (ad_p)^{-2.0}$$

Where

K_5=5.23 for packing sizes above 15mm, and 2.00 for the sizes below 15mm

k_G=gas film mass transfer coefficient, $kmol/m^2s$ bar,

V_w*= gas mass flow rate per unit column cross – section area kg/m^2s,

=7.8472/7.06

=$1.11 kg/m^2s$,

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R=0.08314 bar m^3/kmol K,

T=considering @25^{0}C=298K,

D_v = diffusivity of vapor = diffusivity of air = 22.07 * 10^{-6} m^2/s,

a=actual area of packing per unit volume (see table 11.3), m^2/m^3 =194m^2/m^3,

d_p= packing size, m =38*10^{-3}m,

μ_v= 1.95*10^{-3}kg/ms,

ρ_v= 1.186kg/m^3

Therefore

k_G= 8.04*10^{-4}kmol/m^{2}s bar

G_m= 0.038kmol/m^{2}s,

L_m=2.574kmol/m^{2}s,

The film transfer unit heights are given by:

$H_G=G_m/k_G a_w P$

$H_L=L_m/k_L a_w C_t$

G_m=molar gas flow rate per unit cross sectional area, **G_m**=0.038kmol/m^{2}s,

L_m=molar liquid flow rate per unit cross sectional area, **L_m**=2.574kmol/m^{2}s,

P= column operating pressure, atm or bar,

C_t= total concentration, kmol/m^3=ρ_L/molecular weight solvent =1000/18=55.6mol/m^3

H_G = 0.038/(8.04*10^{-4}*109.72*1.1013)

H_G = 0.43m

H_L = 2.574/(55.6*1.55*10^{-4}*109.72)

H_L = 2.7221m

H_{OG} = 0.43 + 0.7*2.7221 =2.94m

Z=N_{OG}*H_{OG} = 5*2.94= 14.7m approx. = 15m

Results

By using intaloxsaddles as packing material the parameters of column by following methods are:

> i) Cornell's method Z = 18meters
> ii) Onda's method Z= 15meters
> iii) Column diameter D_c = 3meters

By assuming height (z) as 15meters

V.   MATERIAL OF CONSTRUCTION

Determined by application because most contaminants involve corrosive gases and fumes, material must be able to withstand continuous contact with high and low pH gases and scrubbing solutions.

Standard construction materials include polypropylene, PVC and Fiberglass .Optional materials include high alloy metals such as stainless steel and hastelloy. Dual-laminate structures incorporating FRP over PVC, PP, PVDF and Teflon liners are also available.

Fiberglass Reinforced Plastic (FRP): is mostly used because of it is economical, easily fabricated lightweight, and has good resistance to both alkaline and acid environment. Where necessary, a FRP scrubber can be used as liner material for steel equipment which is subject to corrosion.

Cast iron may also be used in pilot plant scrubbing applications or where corrosion problems are not severe. Normal water supplies and air will not cause problems. However NO_2 or similar gases in the fluid being scrubbed will cause the formation of dilute acids which will attack cast iron.

Objectives

- To reduce the NO_2 fumes from 80-100ppm to 50-60ppm.
- HNO_3 obtained as the byproduct, can be reused in the operation again at dissolution there by reducing the cost factor

In addition to this our major focus remained on optimizing the height and diameter of the tower in a given pressure drop. The next challenge was to search a material of construction of scrubber which is economically viable, resistant to corrosion and the chemicals that it is exposed to inside the scrubber, and also able to withstand the required temperature. In order to get more efficiency we can use 5% NaOH as scrubbing agent and increasing the diameter of the scrubber increases the residence time which leads to intimate contact of gas and scrubbing agent.

Through this entire Training period at Nuclear Fuel Complex, we got an immensely extravagant opportunity to get exposed to several techniques and industrial processes which, otherwise, would

have been impossible. We learnt a great deal of knowledge working with the overly helpful people around, thus improving our familiarity with several industrial practices. It further helped us to enhance our experimental skills and hence helped us get exposed to practical understanding.

VI. CONCLUSION

During our study here at NFC, we were exposed to a number of techniques involved in the course of chemical engineering. It was enthralling to see all the operations that we studied in the books actually running in reality. Our project was inclined towards the design of a packed scrubber for absorption of NO_2 fumes which is the exhaust of drier where in, the exhaust gas can be purified before being let out into the atmosphere. It explains the detail process of gas absorption accompanied by chemical reaction with its chemical kinetics.

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