

Design and Evaluation of Separation Towers in Water Treatment Plants

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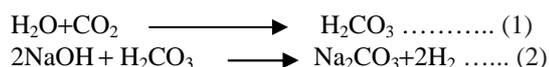
Abstract

Packed columns are used for the removal of contaminated gases such as carbon dioxide from drinking water and industrial wastewater. The packed columns are useful for achieving mass transfer between two phases, gas and liquid. This paper inspects the performance of two separation units. In the first step, the efficiency of the de-carbonator system will be specified, and then the capability of improving the rate of dissolved gas removal by using professional types of packing will be evaluated. The concentration of solute (CO₂) in a dispersed phase (water) has measured as a function of packing height. Also, new correlations for mass transfer coefficient in the gas phase have been predicted. In the second step, the examination of the sedimentation tank performance will be tested, by using the jar test, and then the best chemical additives concentration will be specified. The results show that the rate of dissolved gas removal can be improved when the area of contact between the gas and liquid streams is increased by using the professional types of packing. Also, the accuracy of chemical dosing for polyelectrolyte and ferric chloride in the sedimentation section improves the performance of the pretreatment section and reduces the chemical additives consumption. The backwash processes for sand filters and the period of replacement for fine filters has been improved after regulating the methods of separations.

Key words: Water treatment, de-carbonator, sedimentation, performance.

Introduction

The quality of water production from water desalination systems depends on the efficiency of separation methods. Various separation methods applied, such as sedimentation, adsorption, filtration and decarbonation, in the pretreatment section before desalination processes. Most of these methods depend on mass transfer phenomena. However, water quality varies from place to place and, in any one place, from season to season, and subsequently the resources for construction and operation of a water treatment plant from place to place. So, the selected treatment must be based on a particular situation. Varying amounts of free carbon dioxide (CO₂) are present in natural waters. The amount of CO₂ absorbed by rain water from the atmosphere is very small, ranging from 0.5 ppm to 2 ppm, whereas most surface water contains 0 –5 ppm of CO₂ and groundwater usually contains 1–50 ppm of CO₂¹. The concentration of carbon dioxide is done by titration the sample of water with standard sodium carbonate solution until the color changes to pink where phenolphthalein is used as an indicator. The following reactions will be carried out:



The concentration of CO₂ in the sample is calculated from the formula as follows: CO₂ Concentration (ppm) = $N * \Delta v * 22,000 / \text{ml sample} \dots (3)$

Where N is the normality of sodium carbonate and Δv is the volume of the titration sample (ml). The effects of gases dissolved in distilled water produced by desalination systems include, for example, corrosion problems due to

increased concentrations of these gases, and likewise, the presence of the gases influences the pH values of the water. A separation process, called de-aeration or degasification, is therefore used to remove concentrations of corrosive gases such as oxygen, carbon dioxide, hydrogen sulfide or nitrogen that have been dissolved in distilled water. Carbon dioxide (CO₂) in water may be removed or reduced by means of an aerator, de-gasifier or de-carbonator and may be neutralized by the addition of lime or alkali such as caustic soda, but these procedures are limited to raw or treated waters containing relatively small amounts of CO₂. The performance of the de-carbonator greatly depends on the rate of water flowing through it and the temperature of the water undergoing deaeration². The packed column is useful in carrying out mass transfer between gas and liquid when the fluids pass counter current flow³. A packed column consisting of a vertical vessel and filling with a packed medium has been used to strip the dissolved CO₂ gas via an air stream. The transportation process is achieved due to the difference in partial pressure between the two streams. The mass transfer operation between the two streams is based on the absorption theory, the concept of resistance, and the heat transfer theory⁴. Full treatments of water are important, but none more than settlement, which removes up to 90% of the suspended solids and can affect the performance of the whole treatments probably more than any other single process. Also, not all waters require full treatment and not all treatment plants require settling basins. In any given case the amount of treatment required has first to be decided before considerations have given to the best way of providing it. The aim of the sedimentation process is to reduce the turbidity of water. This can be accomplished

with the aid of two other processes. These two processes include coagulation and flocculation. Different materials can be used as coagulants such as alum, ferric chloride, ferric sulfate, sodium aluminates and lime. The influence of chemical additives with different concentrations on the turbidity removal efficiency can be examined by using a jar test.

Plant description: The de-carbonator rig is designed for removal of CO₂ gas from water by using air as a solvent. The column has dimensions of about 1.2 m as a length and 8 cm as a diameter. The system was tested by using one type of packings. The rig as shown in figure-1 has the following items:

Tower: a plastic column contains number of packings. The main purpose of packing is to improve the contact area between the water and air stream and increase the resident time of water inside the tower. Table-1 shows the general properties of de-carbonator rig.

Table-1
General characteristics of de-carbonator rig

Length	1.2 m
Diameter	0.08 m
Type of packings	Pall rings
Feed flow rate	1-2 Kg/s.m ²
Air flow rate	0.4 -1 Kg/s. m ²

Packings: This is used to improve the mass transfer between two phases. Pall rings were used in de-carbonator tower with two sizes (16 and 25 mm). Table 2 shows the characteristics of Pall rings packing.

Table-2
Packing details

Type	Pall rings	Pall rings
Material	Polypropylene	Polypropylene
Thickness, mm	0.762	1.106
Size ,mm	16	25
Packing factor	97	52
Mass,Kg/m ³	112	88
Surface area, m ² / m ³	341	207
Voidage ,%	87	90

Air compressor: This is used to feed the air to the tower.

Water pump: which is used to pump the water from the storage tank to the top section of the tower, it has a capacity of about 40 liters/min.

Storage tank: which has a capacity about 250 liters.

Flow meter: water and gas flow meters have been used to measure the water and gas flow rates. The liquid and gas flow meters have scales between (0-350 L/min) and (0-250 L/min) respectively.

U-tube manometer: This is used to measure pressure drop in the column.

CO₂ cylinder: This is used to prepare a dilute solution.

Theoretical Steady State Analysis of De-carbonator: In a packed tower, contaminated water flows downward by gravity through a circular column that is filled with randomly packed. Air is introduced into the tower below the packed bed and flows upward through the column counter current to the flow of water. The air dispersed into the bottom of the column (forced draft system). The packing materials designed to maximize specific surface area for contact between the contaminated water and the process air, providing the maximum specific surface area possible for carbon dioxide contaminants to move from the liquid phase to the gas phase. The packing should be wetted completely by the descending liquid in order to provide the maximum amount of active surface area. For this reason, the entering liquid should be distributed uniformly over the top of the packing at a flow sufficient to permit wetting of the entire packing surface. The packing support plate should provide ample space for passage of both liquid and gas with a good distribution of the gas. The analysis of this model is based on the film model⁶. This model is still the most widely used method in the calculation of de-carbonator systems. Contaminated water comes into the tower, as shown in figure 2, from the top section. The inlet concentration of solute in water stream (x_2) while the outlet concentration is (x_1). On the gas side, air comes to the tower with (y_1) where enter the tower at the bottom and leaves the tower, at the top with (y_2). In this case, operation process is carried out at constant pressure and constant temperature. Also, the system can be considered as a dilute system.

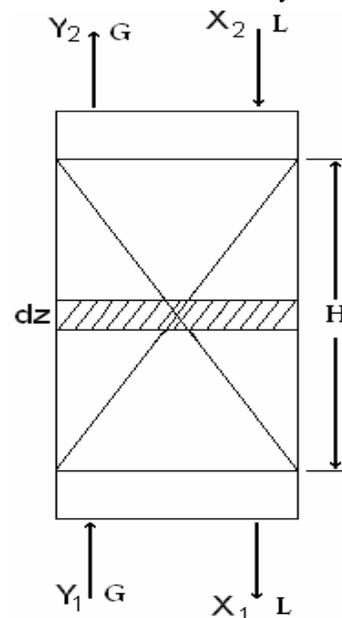


Figure-2
Shows schematic diagram of De-carbonator column

Table -3
Multiple nonlinear regressions for Pall rings
(Experimental Values)

I	K _{G.a}	G	L
1	0.00134	0.4	1.00
2	0.001513	0.4	1.20
3	0.001676	0.4	1.40
4	0.001832	0.4	1.60
5	0.001981	0.4	1.80
6	0.002125	0.4	2.00
7	0.001546	0.6	1.00
8	0.001745	0.6	1.20
9	0.001934	0.6	1.40
10	0.002113	0.6	1.60
11	0.002286	0.6	1.80
12	0.002452	0.6	2.00
13	0.001711	0.8	1.00
14	0.001932	0.8	1.20
15	0.00214	0.8	1.40
16	0.002339	0.8	1.60
17	0.00253	0.8	1.80
18	0.002713	0.8	2.00

Values of regression coefficients
a₁= 1.8509E-03
b₁= 3.5244E-01
c₁= 6.6527E-01

The following equation can be used to describe the liquid phase⁷:

$$L \frac{dx}{dz} = K_L \cdot a \cdot A_c (x - x^*) \quad \dots\dots(4)$$

Also, for the gas phase [1]:

$$G \frac{dy}{dz} = K_L \cdot a \cdot A_c (x - x^*) \quad \dots\dots(5)$$

Since, $y = mx^*$ (at interface) $\dots\dots(6)$

Where $m = H_o/P$

Subs. x* from equation 6 in equations 4 and 5

$$G \frac{dy}{dz} + K_L a A_c \left(x - \frac{y}{m} \right) = 0 \quad \dots\dots(7)$$

Table -4
Multiple nonlinear regression for Intalox saddle
(Theoretical Values)

I	K _{G.a}	G	L
1	0.004056	1	3.00
2	0.004357	1.2	3.00
3	0.004629	1.4	3.00
4	0.004878	1.6	3.00
5	0.005109	1.8	3.00
6	0.00438	1	3.40
7	0.004705	1.2	3.40
8	0.005	1.4	3.40
9	0.005268	1.6	3.40
10	0.005517	1.8	3.40
11	0.00469	1	3.80
12	0.005038	1.2	3.80
13	0.005352	1.4	3.80
14	0.00564	1.6	3.80
15	0.005907	1.8	3.80

Values of regression coefficients
a₁= 2.0658E-03
b₁= 3.9261E-01
c₁= 6.1414E-01

and $L \frac{dx}{dz} + K_L a A_c \left(x - \frac{y}{m} \right) = 0 \quad \dots\dots(8)$

From equation 8:

$$y = \frac{mL}{k_L a A_c} \frac{dx}{dz} + mx \quad \dots\dots(9)$$

Then the differentiation of equation 9 with respect to z gives:

$$\frac{dy}{dz} = \frac{mL}{k_L a A_c} \frac{d^2x}{dz^2} + m \frac{dx}{dz} \quad \dots\dots(10)$$

Substitute dy/dz from equation 10 and y from equation 9 in equation 7 gives:

$$\frac{mGL}{K_L a A_c} \frac{d^2x}{dz^2} + mG \frac{dx}{dz} + K_L a A_c \left(x - \frac{L}{K_L a A_c} \frac{dx}{dz} - x \right) = 0 \quad \dots\dots(11)$$

Further simplification gives:

$$\left(\frac{L}{K_L a A_C}\right) \frac{d^2 x}{dz^2} + \left(1 - \frac{L}{mG}\right) \frac{dx}{dz} = 0 \quad \dots\dots (12)$$

Assume $\left(1 - \frac{L}{mG}\right) = \beta$

And $\frac{L}{K_L a A_C} = \alpha = HTU$

This gives:

$$\alpha \frac{d^2 x}{dz^2} + \beta \frac{dx}{dz} = 0 \quad \dots\dots (13)$$

Or; $\alpha n^2 + \beta n = 0 \quad \dots\dots(14)$

Then the solution of equation 14 is:

$$x = A e^{n_1 z} + B e^{n_2 z} \quad \dots\dots(15)$$

Where;

$$n_1 = 0 \quad \text{and} \quad n_2 = -\beta / \alpha$$

Subs. these roots in equation 15 give

$$x = A + B e^{-(\beta / \alpha) z} \quad \dots\dots(16)$$

The boundary conditions are :

At $Z=0$, $x = x_2$ (B.C.1)

At $Z=H$, $y = y_1$ (B.C.2)

Therefore equation 16 becomes:

$$x_2 = A + B \dots\dots(B.C.1) \quad \dots\dots(17)$$

Taking dx/dz for both sides of equation 17

$$dx/dz = -\frac{\beta}{\alpha} B e^{-(\beta/\alpha)z} \quad \dots\dots(18)$$

So, the equation 9 can be written as follows:

$$y = \frac{mL}{K_L a A_C} \left(-\frac{\beta}{\alpha} B e^{-(\beta/\alpha)z}\right) + mx \quad \dots\dots(19)$$

Substitute (B.C.2) in equation 19 gives:

$$y = 0 = \frac{-mL}{K_L a A_C} \frac{\beta}{\alpha} B e^{-(\beta/\alpha)H} + mx \quad \dots\dots(20)$$

And, $x_{Z=H} = \frac{L}{K_L a A_C} \left(\frac{\beta}{\alpha}\right) B e^{-(\beta/\alpha)H} \quad \dots\dots(21)$

By equating the two equation 21 and 16

$$A + B e^{-(\beta/\alpha)H} = \frac{L}{K_L a A_C} \left(\frac{\beta}{\alpha}\right) B e^{-(\beta/\alpha)H} \quad \dots\dots(22)$$

Then, substitute A from equation 17 in 22

$$\begin{aligned} (x_2 - B) + B e^{-(\beta/\alpha)H} &= x_2 - B(1 - e^{-(\beta/\alpha)H}) \\ &= \frac{L}{K_L a A_C} \left(\frac{\beta}{\alpha}\right) B e^{-(\beta/\alpha)H} \end{aligned}$$

$$B = \frac{x_2}{1 - \left(1 - \frac{L}{K_L a A_C} \left(\frac{\beta}{\alpha}\right)\right) e^{-(\beta/\alpha)H}} \quad \dots\dots(23)$$

Substitute β and α values in equation 23 gives:

$$B = \frac{x_2}{1 - \frac{L}{mG} e^{-(\beta/\alpha)H}}$$

Also, subs. B in equation 17 gives:

$$\begin{aligned} A = x_2 - B &= x_2 - \frac{x_2}{1 - \frac{L}{mG} e^{-(\beta/\alpha)H}} \\ &= \frac{-x_2 \frac{L}{mG} e^{-(\beta/\alpha)H}}{1 - \frac{L}{mG} e^{-(\beta/\alpha)H}} \end{aligned}$$

Substitute A and B in equation 16 gives:

$$\frac{x}{x_2} = \frac{e^{-(\beta/\alpha)z} - M e^{-(\beta/\alpha)H}}{1 - M e^{-(\beta/\alpha)H}} \quad \dots\dots(24)$$

Where $M = \frac{L}{mG}$

So, equation 24 can express as a function of concentration:

$$\frac{C}{C_o} = \frac{e^{-(\beta/\alpha)z} - M e^{-(\beta/\alpha)H}}{1 - M e^{-(\beta/\alpha)H}} \quad \dots\dots(25)$$

The above equation, will use for calculating the outlet concentration of solute as a function of packing height.

Mass Transfer Coefficient in Gas Phase: This section deals with developing a new correlation for predicting the values of mass transfer coefficient as a function of gas and liquid flow rates. Previously, various equations have been derived under specific conditions. Consequently, a new correlation will be derived relative to the present de-carbonator diameter.

The general form of new correlation is:

$$K_G \cdot a = a_1 * L^{b_1} * G^{c_1} \quad \dots\dots (26)$$

Where a_1 , b_1 , and c_1 are new constants

By take a logarithm of both sides for equation 26, it becomes:

$$\ln K_G \cdot a = \ln a_1 + b_1 \ln L + c_1 \ln G \quad \dots\dots(27)$$

Or; $\psi = \eta_1 + \eta_2 \tau_1 + \eta_3 \tau_2 \quad \dots\dots(28)$

Where

$$\psi = \ln K_G \cdot a, \quad \eta_1 = \ln a_1, \quad \eta_2 = b_1, \quad \tau_1 = \ln L,$$

$$\eta_3 = c_1, \quad \tau_2 = \ln G$$

For solving equation 28 by using nonlinear regression method, the j equations for the j experimental measurements can be expressed in matrix form as:

$$\begin{bmatrix} 1 & \tau_{11} & \tau_{12} \\ 1 & \tau_{21} & \tau_{22} \\ 1 & \tau_{31} & \tau_{32} \end{bmatrix} \begin{bmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \end{bmatrix} = \begin{bmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{bmatrix}$$

The above matrix is solved by a computer program for calculating the coefficients a_1 , b_1 , and c_1 of equation 26. Tables 3 and 4 show the values of regression coefficient of $K_G \cdot a$ for different values of liquid and gas flow rates, and for both types of packing, Pall rings and Intalox saddle. The following equations show the values of regression coefficient for $K_G \cdot a$ for different values of liquid and gas flow rate, and for both types of packing Pall rings and Intalox saddle

$$K_G \cdot a = 1.8509 \times 10^{-3} G^{0.35244} L^{0.66527}$$

(For Pall rings) (29)

$$K_G \cdot a = 2.0658 \times 10^{-3} G^{0.39261} L^{0.61414}$$

(For Intalox saddle) (30)

The above two equations are used to calculate the theoretical of gas mass transfer coefficient for two type of packing (Pall rings and Intalox saddle).

Results and discussion

The concentration profile of solute in water phase along the packing height for each types of packing can be evaluated by using equation 25. This equation shows the concentration of solute as a function of packings height, flow rate of both phases, physical properties of liquid phase, and inlet concentration. Figure 2 and 3 shows the exponential relation between carbon dioxide concentrations as a function of packing height. Also, it's clear that the performance of Pall rings packing for removing dissolved gas (CO_2) is higher than Intalox saddle, this is due to its lower wettability and higher void fraction (0.87, 0.90) for both sizes of pall rings packing (16 and 25mm). Also, figures 2 and 3 shows the inverse relation between liquid flow rate and carbon dioxide removal. For Pall rings packing, 16 mm, height of packings is equal to 0.2 m; and water flow rate varied between 1 to 2 Kg/s.m^2 . So, the CO_2 concentration in the effluent stream will be increased from 3.5 to 3.7 ppm. This means the CO_2 removal efficiency is reduced by about (26%) while for 25 mm Pall rings the efficiency of CO_2 removal has improved to (30%). The same behavior occurs when Intalox saddle was used. The value of CO_2 removal has reduced about (19%) by using 16 mm Intalox saddle, while for 25 mm Intalox saddle, the value of CO_2 removal has improved to (22%). The main reason for the inverse relation between liquid flow rate and CO_2 removal efficiency is due to the reduction of contact time between the gas and liquid phase so; the ability of CO_2 transfer from liquid phase (water) to gas phase (air) will be decreased. A comparison study between theoretical and experimental results for 16 and 25 mm Pall rings had been carried out. The results show a good agreement between them where the maximum error does not exceed (6.25%) for 16mm Pall rings and 8.33 %

for 25 mm Pall rings. The air flow rate is considered as a one of the important operation conditions, which has a large effect on the de-carbonator tower efficiency. The air flow rate affects the de-carbonator efficiency by raising the resistance of air to the water flow. Consequently, the dissolved gas (CO_2) will remain a longer time inside the tower then; the probability of mass transfer between the two phases will be improved. Figures 5 and 6 depict the relation between the air flow rate and gas mass transfer coefficient. Figure 4 shows when Pall rings are used with air flow rate varying between (0.4-1) Kg/s.m^2 with height of packings equal to 0.65m and liquid flow rate is 1 Kg/s.m^2 , so, the mass transfer coefficient in air phase have varied between (0.001340-0.001851) Kg/s.m^2 . For Intalox saddle with air flow rate varying between (1-2) Kg/s.m^2 with the packing height is 0.65m and liquid flow rate is 3 Kg/s.m^2 so, the values of mass transfer coefficient in air phase have varied between (0.004-0.00487) Kg/s.m^2 . The results show when the air and liquid flow rate increases so, the mass transfer coefficient in gas phase will be increased for both types of packings. The results for mass transfer coefficient in gas phase have been obtained by using a new correlation for both types of packings (Pall rings, Intalox saddle) as they are described in equations 29 and 30. However, for both types of packings, there are proportional relations between the air flow rate and the mass transfer coefficient in gas phase.

Sedimentation process: The aim of this part is to establish the appropriate dosage of two types of coagulants (alum and polyelectrolyte) for removing the turbidity of raw water. The raw water represents the Tigers River water with TDS equal to 750 ppm and turbidity of about 18 NTU. Alum and polyelectrolyte are mixed with distilled water inside two mixing tanks separately, the two tanks are provided with one vertical shaft mixer which is connected to a driving motor which has a variable speed control. The alum and polymer solutions are injected also separately (at the same time) to the sedimentation tank by using two dosing pumps. The flow rate of injection of both pumps is 6 l/h, but the concentration of each solution is different. However, the concentration of alum and polymer solutions is changed from 15 to 28 ppm and 0.58 respectively. The percentage of turbidity removal was calculated by the following equation:

$$\% \text{ removal} = \frac{[\text{turbidity}_1 - \text{turbidity}_2]}{\text{turbidity}_1} \times 100 \quad \dots (31)$$

Where turbidity 1 and 2 are represents the turbidity of raw and treated water respectively. The chemical structure of alum is $\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$ and when alum is added to the raw water, small floc particles are formed inside the treated water. This leads to an increase in the settling velocity of particles and subsequently a decrease in the turbidity values for the water to about 5 NTU when the concentration of alum about 28.6 ppm. For improving the rate of sedimentation and the quality of treated water, alum and polymer are added alternatively. Different concentrations of coagulants have been chosen for specifying the influence of coagulant on the turbidity

values of treated water. When alum is added to raw water at the initial speed of mixer of 100 rpm, and after the small floc particles are formed the polymer is added at the speed of mixer of 20 rpm. The results show that the values of turbidity are improved by using this method. The value of turbidity is reduced from 18 NTU to 1 NTU by using 22.9 ppm of alum and 4.57 ppm of polymer. This is due to the

effectiveness of the polymer that contains long chain molecules with a large number of charged (negative) groups, where the small floc particles are aggregated by the polyelectrolyte to yield the large floc by chemical bridging, so that the large floc leads to increasing the settling velocity and increasing the effectiveness of the coagulation process. Also, alum and polyelectrolyte are added together,

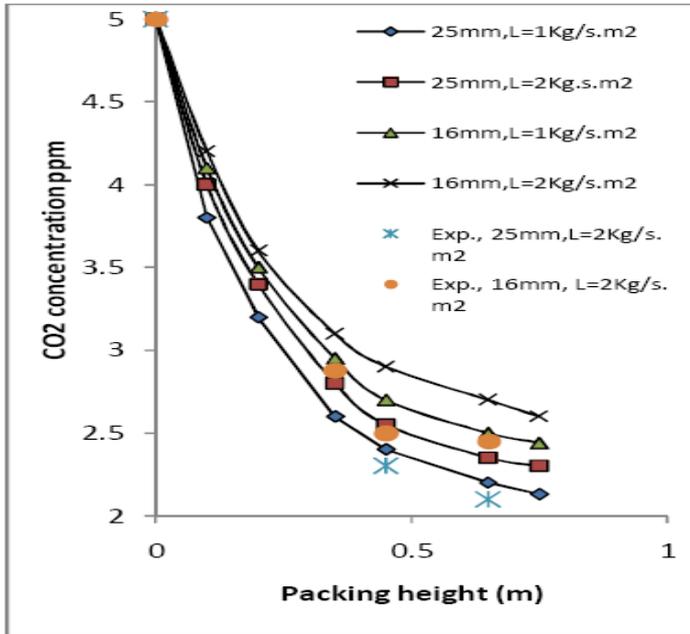


Fig.(3) CO₂ concentration on water phase as a function of packing height for pall rings packing

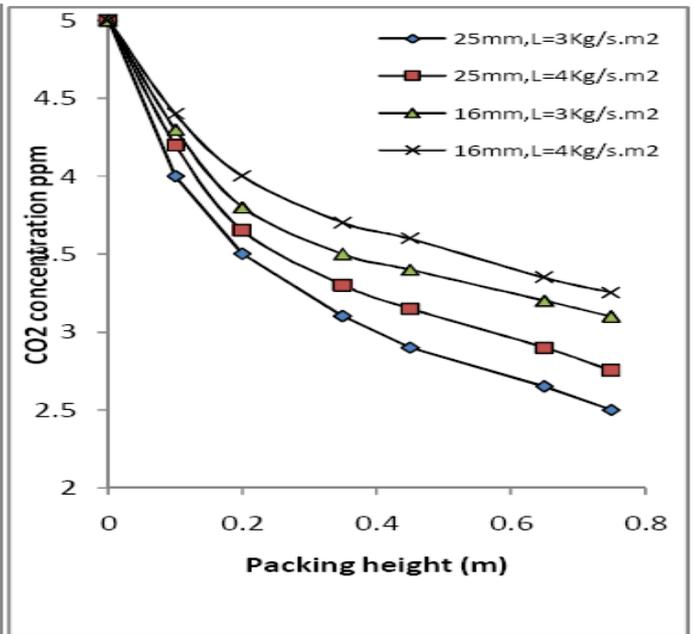


Fig.(4) CO₂ concentration on water phase as a function of packing height for Intalox saddle packing

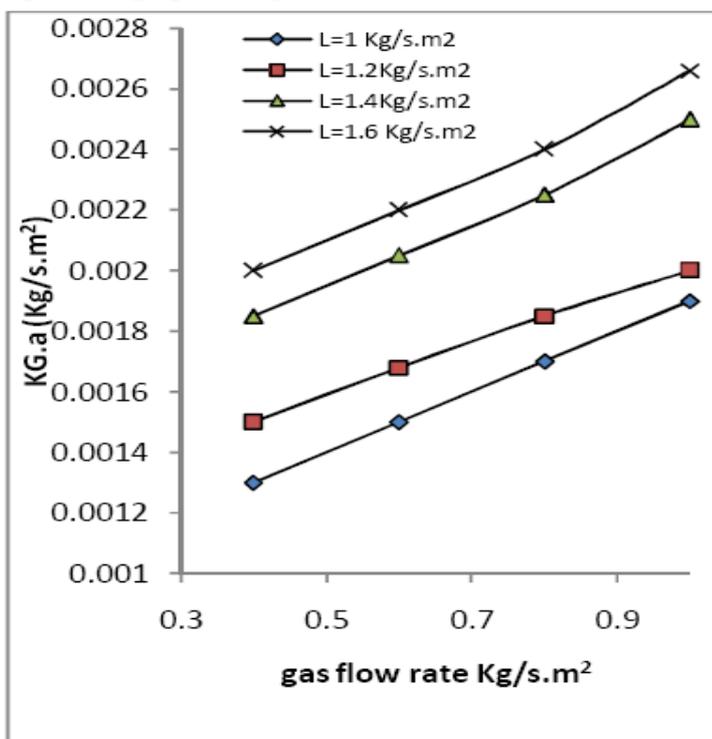


Fig.(5) gas mass transfer coefficient versus gas flow rate for pall rings packing, packing height=0.65m

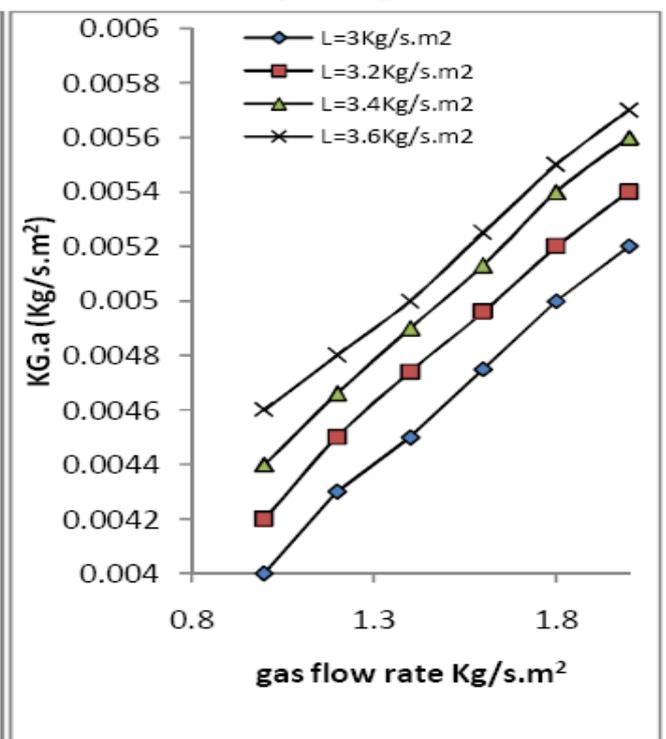


Fig.(6) gas mass transfer coefficient versus gas flow rate for Intalox saddle packing, packing height=0.65m

but at the same time and at the same initial mixer speed — 100 rpm. The results show that the values of turbidity for treated water are greater compared with the previous method. Using this method of addition, the floc particles inside the raw water are formed, but the results show that the size of floc is less than that in the previous method.

Conclusions

A new design equation describing the concentration profile a long packed bed column and containing all the parameters needed for design these column has been obtained. The effect of air flow rate on the gas mass transfer coefficient has calculated by using the prediction equations.

The results show the proportional relation between air flow rate and gas mass transfer coefficient. The effect of packing height on the CO₂ removal have evaluated for various types of packing .The results show the exponential relation between them. The performance of Pall rings packing for removing of CO₂ was higher than Intalox saddle. The values of CO₂ removal by using Pall rings (16 and 25 mm) and Intalox saddle (16 and 25 mm) were (26%, 30% ,19% ,22%) respectively.

The results show that injecting alum and polymer to raw water separately at different times is better than addition of chemical additives at the same period.

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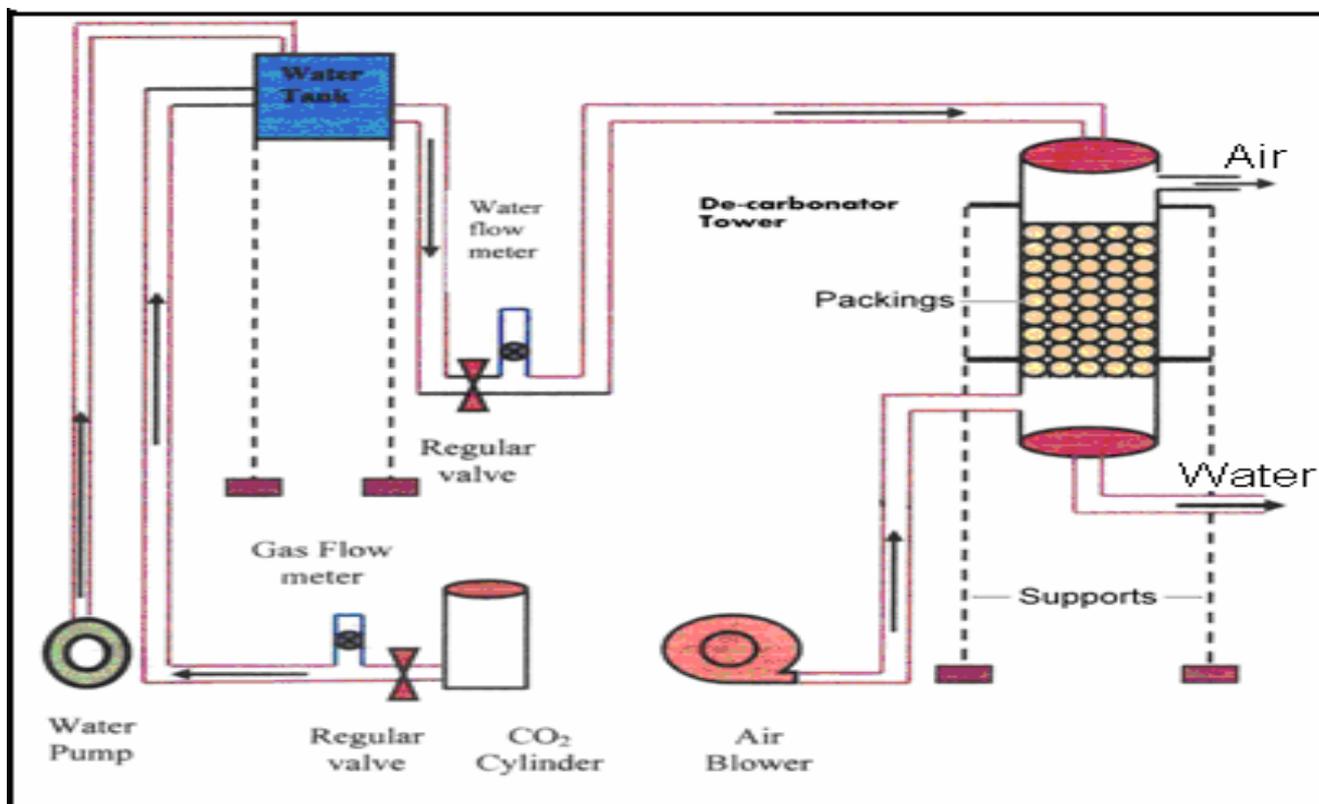


Figure-1
The Schematic diagram of the de-carbonator rig

List of Symbols

Symbols		
	Description	S. I. Units
A	Constant	
A _C	Cross-sectional area of tower	m ²
a ₁	Constant	
a _p	Total area of packing per unit	m ² /m ³
B	Constant	
b ₁	Constant	
C	concentration for CO ₂ in liquid phase change with packing height	ppm
C _i	Concentration of CO ₂ in liquid	ppm
C _{Li1}	Interfacial concentration of CO ₂ in liquid phase	ppm
C _{Li2}	Interfacial concentration of CO ₂ in gas phase	
C _{L1}	Inlet concentration for any solute in liquid phase	ppm
C _{L2}	Outlet concentration for any solute in gas phase	ppm
C ₀	Initial CO ₂ concentration inlet to de-carbonator tower (unsteady state period)	ppm
c ₁	Constant	
D _L	Diffusivity of liquid phase	m ² /s
d _p	Equilibrium diameter of packing element	mm
G	Gas flow rate	kg/m ² .s
g	Gravitational constant	m/s ²
H	Height of packed bed	m
H ₀	Henry's constant	atm/wt %
K _{G,a}	Overall gas mass transfer	Kg/m ² .s
K _{L,a}	Overall liquid mass transfer	Kg/m ² .s
k _{G,a}	individual gas mass transfer	Kg/m ² .s
k _{L,a}	individual liquid mass transfer coefficient	Kg/m ² .s
L	Liquid flow rate	Kg/m ² .s
m	Distribution coefficient	
P	Atmospheric pressure	N/ m ²

Symbols		
	Description	S. I. Units
T	Operating temperature	°C
t	Time	s
V	Volume of titration	ml
Wt	Weight fraction	%
x	CO ₂ concentration in liquid phase (weight fraction)	
x ₁	Outlet CO ₂ concentration in liquid phase (weight fraction)	
x ₂	Inlet CO ₂ concentration in liquid phase (weight fraction)	
x [*]	Equilibrium in liquid phase (weight fraction)	
y	CO ₂ concentration in gas phase (weight fraction)	
y ₁	Inlet CO ₂ concentration in gas phase (weight fraction)	
y ₂	Concentration of CO ₂ in the out let gas phase (weight fraction)	
y [*]	Equilibrium in gas phase (weight fraction)	
Z	Total height of the packed bed	m
Z	Variable height of the packed bed	m
α	Constant	
β	Constant	gm/cm.s
μ	Viscosity	
ε	Fractional voids in dry packing	
η	Constant	
ψ	Constant	kg/ m ³
ρ	Density	
λ	Constant	m/s
v	Velocity	
τ	Constant	