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# MASS TRANSFER COEFFICIENTS IN AN ABSORBER REACTOR IN THE UNIT OPERATIONS LABORATORY (1)

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## ABSTRACT

*In the Unitary Operations laboratory of the Faculty of Chemistry of the UNAM, in Mexico City, students experimentally obtain the mass transfer coefficients in the presence of chemical reaction in a reactor-absorber by using a chromatograph for gases of the electrical conductivity type. In the present article the experiment carried out by the students is shown where the calculation procedure was programmed for computer. Previously they made several studies to catalog the reactive system and choose the equations and the theory that must be applied to reach the desired results and obtain the individual and temporary coefficients of mass transfer in the presence of the chemical reaction of the gas side and the liquid. This type of experiment reinforces the teaching of the necessary skills that a chemical engineer must possess.*

**KEYWORDS:** *Absorption with chemical reaction, enhancement factor or reaction coefficient E, Hatta number, pseudo-first-order reaction. MEA-H<sub>2</sub>O / CO<sub>2</sub>-air reactant system. Teaching by competences.*

## 1.-INTRODUCCIÓN

The teaching of chemical engineering today is based on the so-called competencies. The professional competences are those that are learned during the race and that include the specific knowledge of the same one, as well as the abilities and the professional attitudes of the students. The Laboratory of Chemical Engineering of the UNAM is one of the places where these competences can be developed and perfected through the development of practices, since during these experiments the students have to use their knowledge and apply them, as well as develop their personal skills and attitudes. In that laboratory, unit operations are studied among other disciplines. There Chemical Engineering students experiment in different equipment, one of which is the absorption tower. In it, students are asked to find experimentally the individual mass transfer coefficients of the gas and liquid side respectively in the presence of a chemical reaction.

## 2.- THEORETICAL FOUNDATIONS

To determine the specific absorption-reaction parameters of the monoethanolamine system dissolved in water and the gaseous phase formed by air with carbon dioxide (MEA-H<sub>2</sub>O / CO<sub>2</sub>-AIR) an absorption tower located in the Chemical Engineering Laboratory was used .

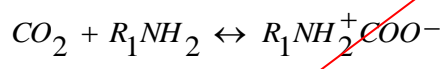
For this, it was necessary to consider the operating conditions used, make observations and consider possible theoretical and practical simplifications. For example:

- The reaction is fast enough to develop in the liquid film.
- The reaction is exothermic
- The enhancement factor should be evaluated to see how the coefficient of the liquid phase of a possible physical absorption is modified.
- The number of Hatta must be evaluated to see what is the controlling mechanism between the diffusion and the reaction along the column.
- It must be found if, under the experimental conditions, in the absorption tower the reaction is totally reversible.
- The experimental results must be applied to ensure the order of the reaction and its possible simplifications.

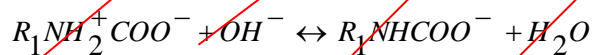
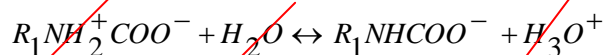
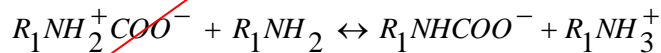
### 2.1.- The reactive system MEA-H<sub>2</sub>O / CO<sub>2</sub>-AIR

In the articles by Jamal [4], [5] the following mechanism is published for the MEA-H<sub>2</sub>O / CO<sub>2</sub>-AIR reactant system, except for the last reaction. We propose it to obtain the representative reaction of this whole mechanism and we find that by adding the terms we obtain the reaction published in the book by Danckwerst [2], Hikita [6] and various authors.

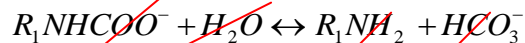
#### MEA-zwitterion formation:



#### MEA-zwitterion deprotonation:



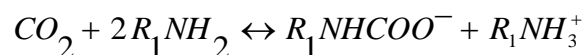
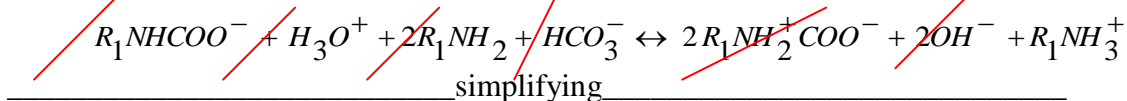
#### MEA-carbamato reversión:



#### MEA-deprotonation:



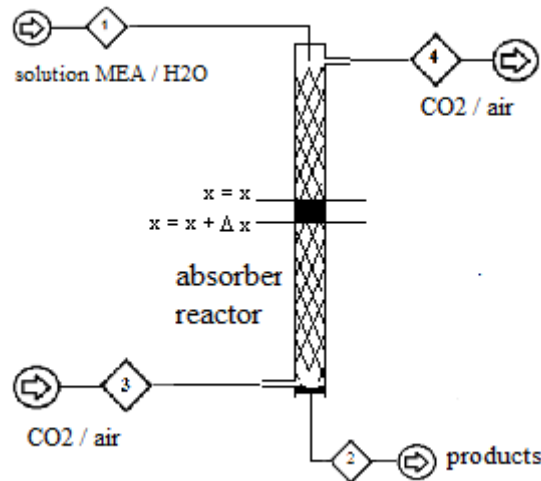
#### Formation of Carbamic ion and the Amine ion



The above reaction is of second order and has a reaction rate constant of:

$$k_2 = 10200 \frac{L}{\text{gmol s}} \text{ at } 30^\circ\text{C} \text{ [5]}$$

**2.2 -** The proposed reactor-absorber model for the reaction between the absorbed carbon dioxide and the monoethanolamine in the liquid phase is as shown in Fig.(1):



**Fig.(1)** Absorber Reactor

Assumptions:

- (a) The reaction is homogeneous and pseudo-first order with respect to solute A (CO<sub>2</sub>).
- (b) The longitudinal velocity of the liquid is constant, there is no radial or angular velocity.
- (c) Radial mixing is perfect, there are no radial concentration gradients.
- (d) The axial diffusion is negligible, in comparison with the convective axial effects.
- (e) The density of the system is practically constant.
- (f) The volumetric molar concentration of the soluble gas in the bulk of the liquid in the column  $[A_0] = 0$ , all the CO<sub>2</sub> reacts in the film.
- (g) The molar volumetric concentration of solute A at the interface  $[A^*]$  of the liquid side in equilibrium with the gas phase is the same at all points in the column.
- (h) The change in the partial pressure of the CO<sub>2</sub> mixed with the dry air within the absorber reactor, is linear along the column.
- (i) There are no radial or angular molar fluxes in the reactor-absorber, only longitudinal and temporal.
- (j) The control of mass transfer resides in the liquid phase.

From Fig.1 the following differential balance can be made for CO<sub>2</sub> in the liquid phase in the absorber reactor:

$$\begin{aligned}
 -D_L \varepsilon S \left. \frac{\partial [A_0]}{\partial x} \right|_x + \varepsilon S L [A_0] \Big|_x + z R_A a \Delta x S &= -D_L \varepsilon S \left. \frac{\partial [A_0]}{\partial x} \right|_{x+\Delta x} + \\
 \varepsilon S L [A_0] \Big|_{x+\Delta x} + \varepsilon S \Delta x \frac{\partial [A_0]}{\partial t} - r \varepsilon S \Delta x & \quad (1)
 \end{aligned}$$

Dividing between the control volume ( $\varepsilon S \Delta x$ ) and taking limits you get:

$$L \frac{\partial [A_o]}{\partial x} + \frac{\partial [A_o]}{\partial t} - \frac{z R_A a}{\varepsilon} - r = D_L \frac{\partial^2 [A_o]}{\partial x^2} \tag{2}$$

convection   accumulation   Absorption   reaction   diffusion  
with reaction

Using the differential balance of equation (2) if there is no accumulation, and neglecting the convective and diffusive terms of the absorbed CO<sub>2</sub>, but considering that there is an appreciable reaction in the film and the speed of absorption with reaction is appreciably greater than the speed of physical absorption is had:

$$- \frac{z R_A a}{\varepsilon} - r = 0 \tag{3}$$

The differential balance for the amine is

$$L \frac{\partial [B_o]}{\partial x} = -r \tag{4}$$

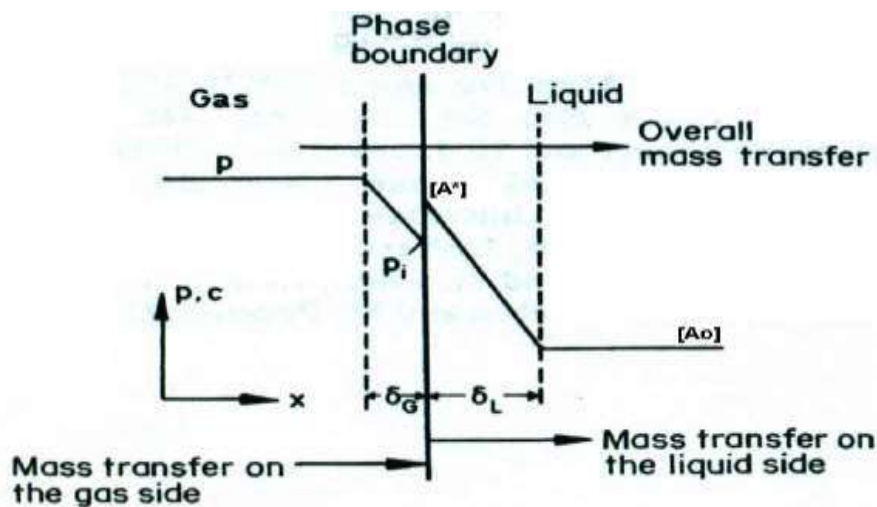
Matching (3) and (4) you get

$$L [B_o] = z \frac{R_A a}{\varepsilon} dx \tag{5}$$

Integrating equation (5) up to the height H of the reactor-absorber

$$H = \frac{L \varepsilon}{z a} \int_{B_o \text{ bottom}}^{B_o \text{ top}} \frac{d [B_o]}{R_A} \tag{6}$$

**2.3.-** Rapidity of mass transfer with chemical reaction through the interface using the model of the film Fig. (2).



**Fig.(2)** Concentration profiles of the two film model, overall mass transfer by absorption [1]

The flux of the solute that reaches the interface on the gas side is given by

$$R_A a = k_g a (p - p_i) = E k_L a ([A^*] - [A_0]) \tag{7}$$

Si  $p_i = H_e [A^*]$  (Henry law)

$$k_g a (p - H_e [A^*]) = E k_L a ([A^*] - [A_0]) \tag{8}$$

Clearing  $[A^*]$

$$[A^*] = \frac{k_g a p + E k_L a [A_0]}{E k_L a + k_g a}$$

Substituting  $[A^*]$  in equation (7), canceling terms and according to the assumption of the model that there is no reaction in the fluid bulk in the liquid phase,  $[A_0] = 0$  we obtain:

$$R_A a = \frac{p_{CO_2}}{\frac{1}{k_g a} + \frac{H_e}{E k_L a}} \tag{9}$$

#### 2.4.- Effect of Reaction

An increase in the rate of absorption caused by reaction is a result of a dropping of the concentration  $[A_0]$  in the bulk liquid phase and so increasing the concentration difference. This can be regarded as the main reaction effect [1]:

$$j_A = k_L ([A^*] - [A_0]) = -D_A \left( \frac{d[A]}{dx} \right)_{x=0} \tag{10}$$

The concentration gradient at the interface becomes steeper while the mass transfer coefficient  $k_L$  remains unchanged Fig. (3) The film model gives an example of this situation [1].

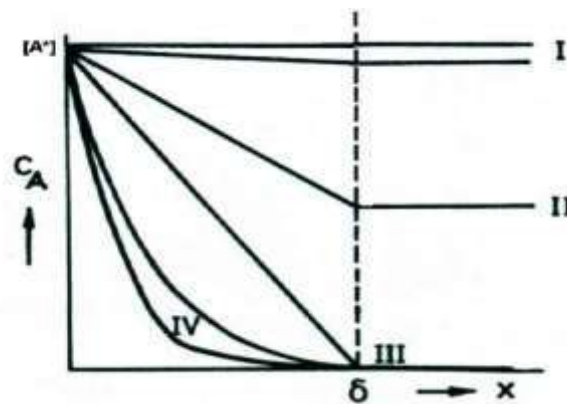


Fig. (3) Interface concentration profiles (film model) [1]

The critical case  $[A^0] = 0$  is denoted as a diffusion regime, provided the concentration gradient over the film is still constant. Depending on the reaction rate and the ratio of the film volume to bulk liquid, considerable reaction may take place in the film leading to an increase in the concentration gradient (IV), this is taken into account by introducing the enhancement gradient factor E (also known as reaction factor), which is defined as follows [1]:

$$E = \frac{j_A}{k_L[A^*]} \tag{11}$$

When the absorption-reaction rate  $R_A$  ( $\text{gmol cm}^{-3} \text{s}^{-1}$ ) is formulated with consideration of the absorption enhancement factor the one obtains for the general case [1]:

$$R_A a = E k_L a ([A^*] - [A^0]) \tag{12}$$

**2.5.- The effective interfacial area "a" per unit of volume packed**

To estimate the effective interfacial area per unit of packed volume, Danckwerst [2] proposes the following equation:

$$\frac{a}{at} = 1 - \exp \left\{ -1.45 \left( \frac{\sigma_c}{\sigma_L} \right)^{0.75} \left( \frac{L}{at \mu_L} \right)^{0.1} \left( \frac{L^2 at}{\rho G^2} \right)^{-0.05} \left( \frac{L^2}{\rho_L \sigma at} \right)^{0.2} \right\} \tag{13}$$

**2.6.- Irreversible first-order reaction, Hatta's number**

When the absorption process is accompanied by a fast irreversible first-order reaction, the bulk concentration is equal to zero. The following balance then results within the film area IV of Fig.(3) in accordance with film theory:

$$D_A \frac{\partial^2 [A]}{\partial x^2} = k_1 [A] \tag{14}$$

And this can be solved by incorporating boundary conditions

$$\begin{aligned} x = 0 & \quad [A] = [A^*] \\ x = \delta & \quad [A] = 0 \end{aligned} \tag{15}$$

The measurable absorption rate  $R_A$  in ( $\text{gmol cm}^{-2} \text{s}^{-1}$ ) can be calculated from the concentration profile

$$R_A = -D_A \left( \frac{d[A]}{dx} \right)_{x=0} \tag{16}$$

And by introducing the solution of equations (15 in 16) one obtains:

$$R_A = k_L [A^*] \frac{\sqrt{M}}{\tanh \sqrt{M}} = E k_L [A^*] \tag{17}$$

In which the Hatta module is:

$$\sqrt{M} = \frac{\sqrt{k_1 D_A}}{k_L}, \quad \text{si } k_L = \frac{D_A}{\delta_L} \tag{18}$$

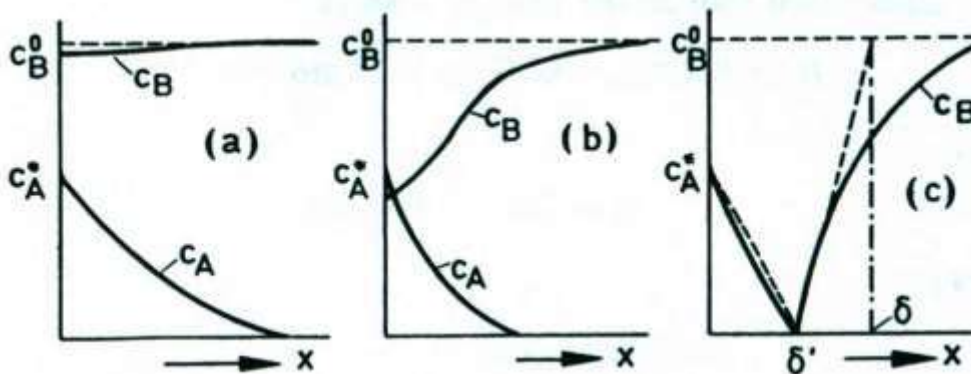
$$\sqrt{M} = \frac{\sqrt{\delta^2 k_1}}{D_A} = \frac{\text{reaction rate in film}}{\text{diffusion rate in film}} \left( \frac{\text{maximum possible conversion in the film}}{\text{maximum transport through the film}} \right) \tag{19}$$

**2.7.- Second-order reaction, Hatta's number**

If a gas component A reacts with a liquid phase component B:



Various situations may arise at the interface and these are shown in Fig. (4). If the concentration of B is large in comparison with [A], then B is not significantly impoverished at the interface and the limiting case (a) reduces to a pseudo-first-order reaction  $k_1 = k_2 [B_0]$ . A further limiting case arises when components A and B react so quickly that they cannot coexist at the same location to any significant extent (instantaneous reaction). [1]



**Fig. (4)** Possible concentration profiles in the region next to the interface for second- order reactions (A+zB→P) [1]

For the general case (b), in which the concentration of B drops distinctly in comparison with the bulk concentration, yet does not reach zero, the film model produces two coupled differential equations which can be solved numerically. Van Krevelen and Hoftijzer have provided an approximate solution [1].

$$\frac{R_A}{k_L [A^*]} = E = \frac{\left( M \frac{E_i - E}{E_i - 1} \right)^{\frac{1}{2}}}{\tanh \left( M \frac{E_i - E}{E_i - 1} \right)^{\frac{1}{2}}} \left( \frac{\text{Absorption rate of A when the reaction occurs}}{\text{Absorption rate of A when there is only mass transfer}} \right) \tag{20}$$

In which



$$M = \frac{D_A k_2 [B^0]}{k_L^2} \tag{21}$$

$$\sqrt{M} = \frac{\sqrt{D_A k_2 [B^0]}}{k_L} \text{ for pseudo first order, si } k_L = \frac{D_A}{\delta_L} \tag{22}$$

$$\sqrt{M} = \frac{\sqrt{\delta_L^2 k_2 [B^0]}}{D_A} = \frac{\text{reaction rate in film}}{\text{diffusion rate in film}} \tag{23}$$

And  $E_i$  is given by equation

$$E_i = 1 + \frac{D_B [B^0]}{z D_A [A^*]} \tag{24}$$

The Van Krevelen and Hoftijzer equation (20) does not give an explicit value for E, hence a great number of other formulae which provide more simple and explicit relations for E have been devised. Further details of these are provided by Wellek et al [3], [1], who also recommended the following explicit equation for the calculation of E:

$$\frac{1}{(E-1)^{1.35}} = \frac{1}{(E_i-1)^{1.35}} + \frac{1}{(E_1-1)^{1.35}} \tag{25}$$

In Which

$$E_1 = \frac{\sqrt{M}}{\tanh \sqrt{M}} \tag{26}$$

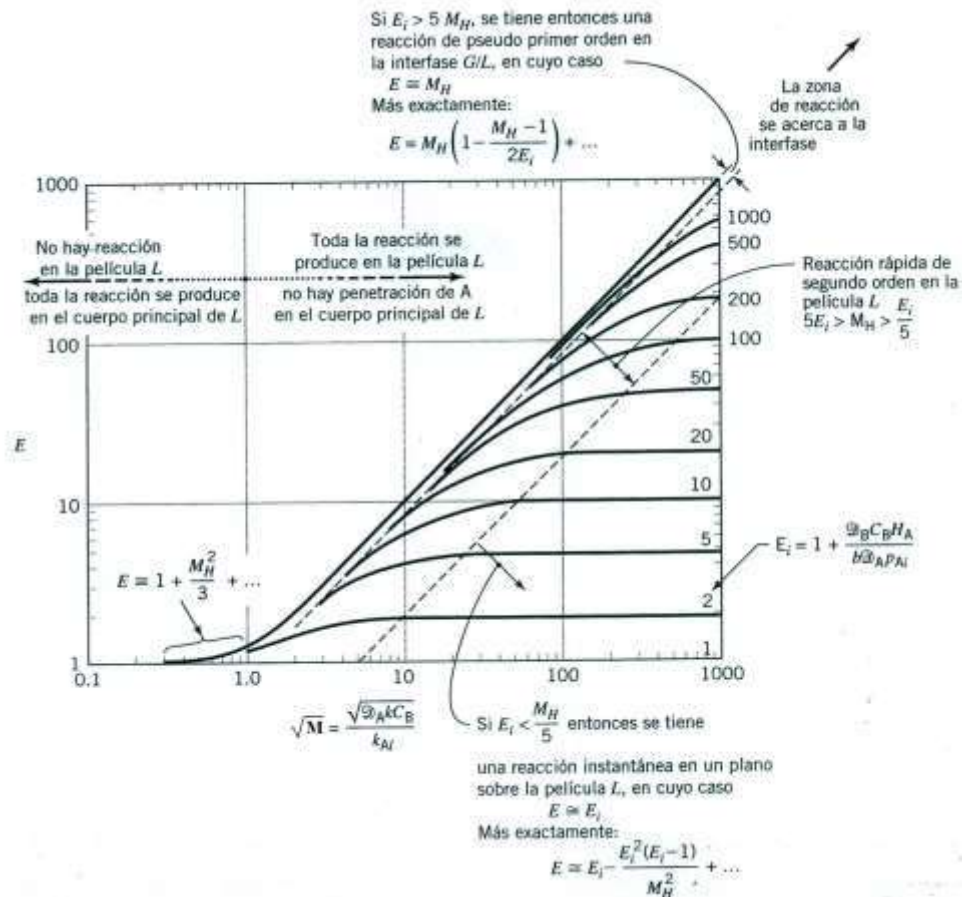
The mean error margin being 1.2% when applying equation (25), [3], [1].

**2.8.- Condition for the reaction to be pseudo-first-order**

In the books of Danckwerst [2], and Wolf-Dieter Deckwer [1] the following expression is found to consider the reaction as pseudo first order

$$\sqrt{D_A k_2 [B^0]} < \frac{1}{2} k_L \left( 1 + \frac{D_B [B^0]}{z D_A [A^*]} \right) \tag{27}$$

And E is near to the limiting diagonal  $E = \sqrt{M}$  and subsequent procedures are based a pseudo-first-order reaction as shown in Fig. (5)

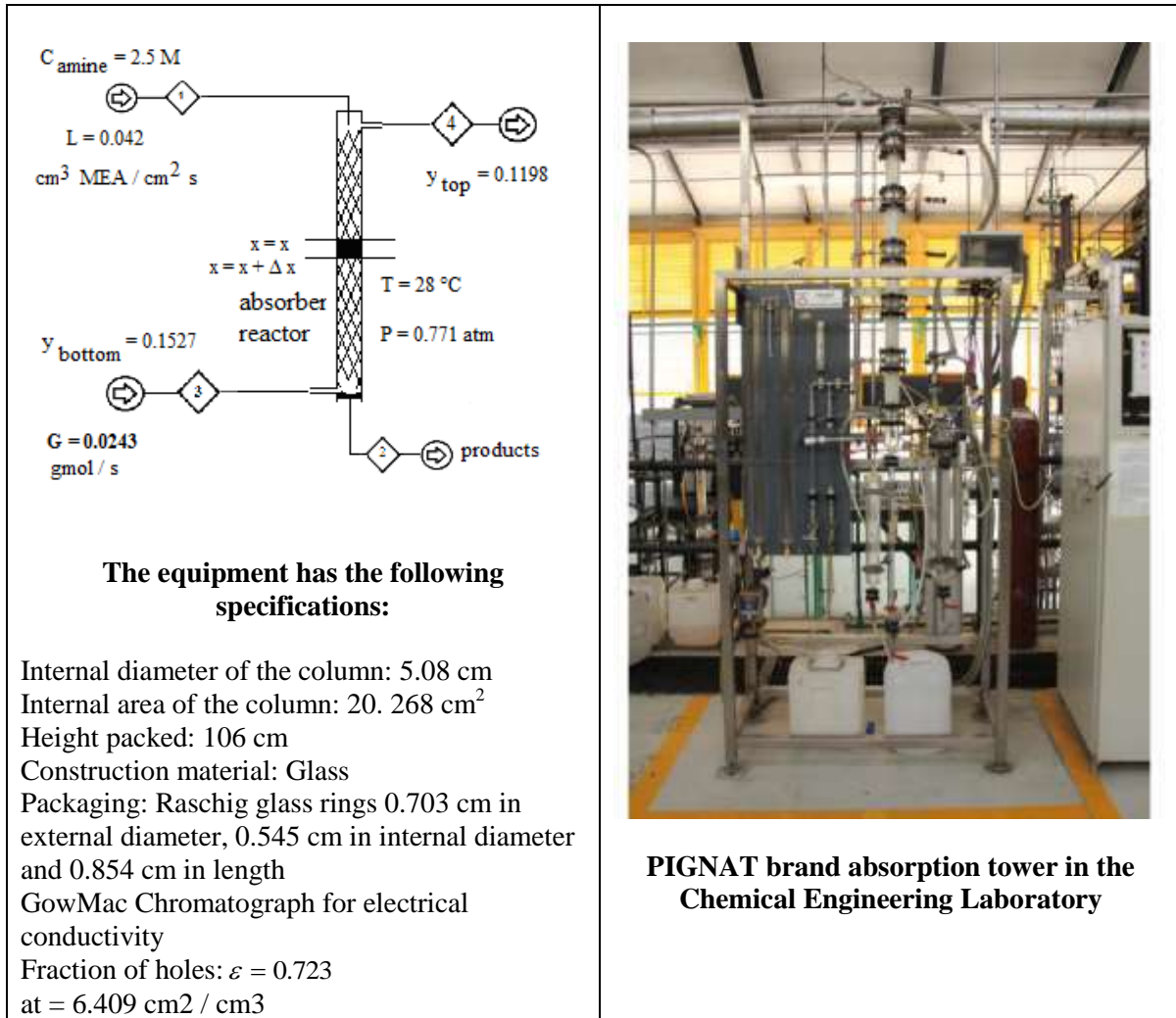


**Fig. (5)** Van Krevelen-Hoftyzer plot enhancement factors in absorption-reaction in function Hatta's Lumber [7].

Also as indicated in Fig. (5), if  $E_i > 5\sqrt{M}$  there is a pseudo first-order reaction close to the gas-liquid interface that is included in the liquid film. As well as the arrow indicating that the entire reaction occurs in the film of the liquid if it is between the value of 1 to 30 of Hatta's number.

### 3.- EXPERIMENTAL DATA AND CALCULATIONS

The equipment used for the experimentation was the following:



**Fig. (6) Absorb-Reactor**

**3.1.-** The following indirect data are estimated values from physical and chemical quantities:

$$K_c = \frac{[RNH_2]^2 [CO_2]}{[RNHCOO^-] [RNH_3^+]} = 9.0 \times 10^{-6} \frac{gmol}{L} \text{ to } (20^o C) [2], [8]$$

$$[A^*] / p = 0.025 \frac{gmol}{L atm} = 2.5 \times 10^{-5} \frac{gmol CO_2}{cm^3 atm} \text{ or } p_i = H_e [A^*], H_e = 40000 \frac{cm^3 atm}{gmol CO_2}$$

reported by Danckwerst[2],[8]

$D_{amine-H_2O} \Big _{\substack{25^{\circ}C \\ 2.5M}} = 7 \times 10^{-6} \frac{cm^2}{s}$ <p><b>Fig. (6)</b></p>	$D_{amine-pure\ water} \Big _{25^{\circ}C} = 10.9 \times 10^{-6} \frac{cm^2}{s}$ <p><b>Fig.(6)</b></p>
$D_{CO_2-H_2O} \Big _{25^{\circ}C} = 1.69 \times 10^{-5} \frac{cm^2}{s} [9]$	$D_{CO_2-H_2O} \Big _{28^{\circ}C} = 1.71 \times 10^{-5} \frac{cm^2}{s} [9]$

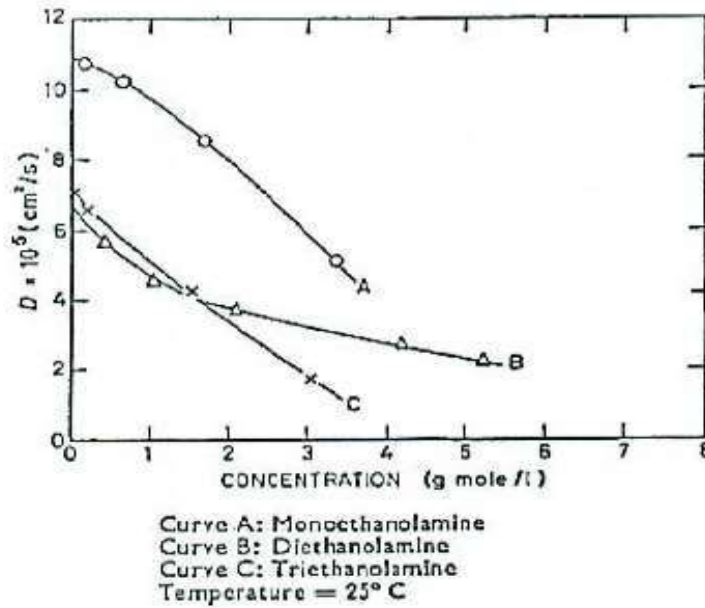


Fig. (6) Diffusion coefficient versus amine concentration, Danckwerst [8]

$$D_A^{28^\circ C} = \frac{D_{am-H2O} \Big|_{2.5 M}^{25^\circ C}}{D_{am-pure\ water} \Big|_{25^\circ C}} \times D_{CO2-H2O} \Big|_{28^\circ C} = 1.09 \times 10^{-5} \frac{cm^2}{s} \quad (\text{for } CO_2)$$

$$D_B^{28^\circ C} = \frac{D_{am-H2O} \Big|_{2.5 M}^{25^\circ C}}{D_{CO2-H2O} \Big|_{25^\circ C}} \times D_{CO2-H2O} \Big|_{28^\circ C} = 0.708 \times 10^{-5} \frac{cm^2}{s} \quad (\text{for } MEA)$$

To estimate  $k_G a$  we used the correlation developed for Norman [8], [10] for the air-ammonia corrected by the Schmidt modules for ammonia-air and CO<sub>2</sub>-air as well as for the operating pressure of the absorber reactor, (where the units of this correlation are in the English system) we have:

$Nsc \Big _{NH3-air}^{28^\circ C} = 0.691$ $P_{operation} = 0.771 \text{ atm}$ $G = \text{lb} / \text{h ft}^2$ $L = \text{lb} / \text{h ft}^2$	$Nsc \Big _{CO2-air}^{28^\circ C} = 0.858$ $P_{operation} = 0.771 \text{ atm}$ $G = \text{lb} / \text{h ft}^2$ $L = \text{lb} / \text{h ft}^2$
---	---

$$k_G a = 0.0142 G^{0.72} L^{0.38} \left[ \frac{Nsc \Big|_{NH3-air}}{Nsc \Big|_{CO2-air}} \right]^{\frac{2}{3}} \times \frac{1}{P_{operation}} \text{ in } \frac{\text{lbmol}}{\text{h ft}^3 \text{ atm}} \quad (28)$$

To evaluate the effective area per unit of packed volume, the equation (13) reported in Danckwerst's text was used [2], (where the units of this equation are in the cgs system) we have:

$\frac{\sigma_C}{\sigma_L} = 0.85$ for water and glass and ceramic packaging $\sigma_C =$ the critical surfase-tension $\frac{dynas}{cm}$ $\sigma_L = 72.754 \frac{dynas}{cm}$ (2.5 M, amine-water) $L = 0.42 \frac{cm^3}{cm^2 s}$ (2.5 M, amine-water) $\mu_L = 0.022$ poises (2.5 M, amine-water)	at = Area of total packing surface per unit of packed volume = $6.409 \frac{cm^2}{cm^3}$ , taken from the manual operation of the absorption column $\rho_G = 9.928^{-4} \frac{g}{cm^3}$ ( $y_{molar CO_2} = 0.1527$ ) $\rho_L = 1.029 \frac{gr}{cm^3}$ (2.5 M, amine-water) <b>Where a = 0.668 cm<sup>2</sup>/cm<sup>3</sup></b>
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3.2.- In an experiment the students obtained the following results shown in the Table (1)

**Table 1)**  
**Experimental data**

Solution temperature = 28 °C		Air temperature = 28 °C		
Internal area of the column: 20.268 cm <sup>2</sup>		Temperature of the CO <sub>2</sub> = 28 °C		
Stoichiometric factor z = 2		P operation = 0.771 atm		
Flow-rate of liquid	Molarity of the amine fed	Fraction mol of CO <sub>2</sub> fed at the bottom of the column	Fraction mol of CO <sub>2</sub> departure	Flow-rate of gas mixture
<b>L = 0.042</b>	$C_{amine} = 2.5 M$	<b>y<sub>bottom</sub> = 0.1527</b>	<b>y<sub>top</sub> = 0.1198</b>	<b>G = 0.0243</b>
$\frac{cm^3 MEA}{cm^2 s}$		$\frac{gmol CO_2}{gmol mixture}$	$\frac{gmol CO_2}{gmol mixture}$	gmol of gaseous feed mixture / s
Flow-rate of insoluble gas	Stechometric factor			
<b>Gs = 0.021</b>	$z = 2$			
gmol of air fed / s				

3.3.- Analysis to determine if the reaction  $CO_2 + 2 R_1NH_2 \leftrightarrow R_1NHCOO^- + R_1NH_3^+$  it is reversible under the operating conditions of Table (1). The following procedure is proposed by Danckwerts [2].

The composition of the liquid at the top of the column is:

$$[MEA] = 2.5 \frac{gmol MEA}{L}$$

$$[RNHCOO^-] = [RNH_3^+] = \frac{2.5 gmol MEA}{L} \times \frac{1 gmol [RNHCOO^-]}{2 gmol MEA} = 1.25 \frac{gmol}{L}$$

The concentration of free CO<sub>2</sub> (unreacted) in equilibrium within the liquid phase at the top of the column

$$A_e = [CO_2] = K_c \frac{[RNHCOO^-] [RNH_3^+]}{[RNH_2]^2}$$

$$= 9.0 \times 10^{-6} \times \frac{1.25^2}{2.5^2} = 2.4 \times 10^{-6} \frac{\text{gmol } CO_2}{L}$$

The back pressure of CO<sub>2</sub> at the interface of the top of the column

$$\frac{[CO_2]}{[A^*]/p} = \frac{2.4 \times 10^{-6}}{0.025} = 9.6 \times 10^{-5} \text{ atm}$$

It can be seen that this value is much lower than the partial pressure of the CO<sub>2</sub> on the gas side, ie; 0.771 atm × 0.1198 fraction mol = 0.09236 atm. Therefore there is not enough counter pressure of CO<sub>2</sub> at the interface, this implies that there is no reversibility of the reaction.

The back pressure at the bottom of the column can be calculated similarly and is totally negligible compared to the partial pressure of CO<sub>2</sub> in the gas:

a) The amount of CO<sub>2</sub> absorbed by the liquid in transit per packing cross section unit:

With the molar fractions  $y_{bottom}$ ,  $y_{top}$ , from Table (1), the corresponding molar ratios can be calculated and the amount of CO<sub>2</sub> absorbed can be obtained

$$CO_2 \text{ Absorbed} = \frac{Gs}{A_{column}} (Y_{bottom} - Y_{top}) = 4.571 \times 10^{-5} \frac{\text{gmol } CO_2}{s \times cm^2}$$

b) The amount absorbed per unit volume of liquid fed

$$\frac{CO_2 \text{ Absorbed}}{L} = 1.083 \times 10^{-3} \frac{\text{gmol } CO_2}{cm^3}$$

c) The composition at the bottom of the column of [MEA] and  $[RNHCOO^-] = [RNH_3^-]$

$$[MEA] = 2.5 \frac{\text{gmol MEA}}{L} - \frac{2 \text{ gmol MEA}}{1 \text{ gmol } CO_2} \times \frac{1.083 \times 10^{-3} \text{ gmol } CO_2}{cm^3} \times \frac{1000 cm^3}{1 L} = 0.334 \frac{\text{g mol MEA}}{L}$$

$$[RNHCOO^-] = [RNH_3^-] = \frac{1.25 \text{ gmol } [RNHCOO^-]}{L} + \frac{1 \text{ gmol } RNHCOO^-}{1 \text{ gmol } CO_2} \times 1.083 \times 10^{-3} \frac{\text{gmol } CO_2}{cm^3} \times \frac{1000 cm^3}{1 L} = 2.333 \frac{\text{gmol } RNHCOO^-}{L}$$

The concentration of free CO<sub>2</sub> (unreacted) in equilibrium within the bulk of the liquid phase at the bottom of the column

$$A_e = [CO_2] = K_c \frac{[RNHCOO^-] [RNH_3^+]}{[RNH_2]^2}$$

$$= 9.0 \times 10^{-6} \times \frac{2.333^2}{0.334^2} = 4.69 \times 10^{-4} \frac{\text{gmol } CO_2}{L}$$

The back pressure of CO<sub>2</sub> at the interface of the bottom of the column

$$\frac{[CO_2]}{[A^*]/p} = \frac{4.69 \times 10^{-4}}{0.025} = 0.019 \text{ atm}$$

while the partial pressure of the CO<sub>2</sub> in the gas in the bottom is 0.771 atm x 0.1527 fraction mol = 0.118 atm therefore there is no counter pressure of CO<sub>2</sub> in the interface

**4.- RESULTS OBTAINED FROM EXPERIMENTATION**

Through successive iterations with the physical absorption coefficient  $k_L$ , the following mass transfer values were found in the presence of chemical reaction on the liquid side, by multiplying these values by the enhancement factor "E" and by the value of the coefficient "a", those of the gas phase were found with equation (28). The result obtained was when the right part of the equation was equated with the height of the column H = 1.06 m. The result was the following and is in the header of the Table (2)

**Tabla (2)  
Results of the iterations**

H = 1.08 m (value obtained from the iterations) Vs. H = 1.06 m (height of the tower), with coefficients  $k_L = 0.016 \text{ cm/s}$  y  $k_G a = 0.000035 \text{ gmol CO}_2 / \text{s cm}^3 \text{ atm}$

$k_L R a =$	$k_G a =$	$H := \frac{L \cdot \epsilon}{z} \cdot \int_{(B_0) \text{ Bottom}}^{(B_0) \text{ Top}} \frac{d(B_0)}{p_{CO_2} \left( \frac{1}{k_G a} + \frac{He}{E \cdot k_L \cdot a} \right)}$
$k_L E a$	$3.5 \times 10^{-5}$	
1 / s	gmol CO <sub>2</sub> / s cm <sup>3</sup> atm	
Bottom 0.043		
0.054		
0.061		
0.066		
Top 0.074		

**Numerical integration of the equation (6)**

[B <sub>0</sub> ]	R <sub>A</sub>	1/R <sub>A</sub>	(1/R <sub>A</sub> ) <sub>MEDIA</sub>	Δ[B <sub>0</sub> ]	∫
gmol / cm <sup>3</sup>	gmolCO <sub>2</sub> / s cm <sup>2</sup>	s cm <sup>2</sup> / gmol CO <sub>2</sub>	s cm <sup>2</sup> / gmol CO <sub>2</sub>	gmol / cm <sup>3</sup>	s / cm
Bottom = 0.00038	1.841 × 10 <sup>-7</sup>	5.431 × 10 <sup>6</sup>			
0.00081	2.176 × 10 <sup>-7</sup>	4.597 × 10 <sup>6</sup>	5.014 × 10 <sup>6</sup>	4.326 × 10 <sup>-4</sup>	2.169 × 10 <sup>3</sup>
0.00124	2.339 × 10 <sup>-7</sup>	4.275 × 10 <sup>6</sup>	4.436 × 10 <sup>6</sup>	4.325 × 10 <sup>-4</sup>	1.919 × 10 <sup>3</sup>
0.00167	2.419 × 10 <sup>-7</sup>	4.134 × 10 <sup>6</sup>	4.205 × 10 <sup>6</sup>	4.259 × 10 <sup>-4</sup>	1.791 × 10 <sup>3</sup>
0.00209	2.440 × 10 <sup>-7</sup>	4.086 × 10 <sup>6</sup>	4.11 × 10 <sup>6</sup>	4.195 × 10 <sup>-4</sup>	1.724 × 10 <sup>3</sup>
Top = 0.00250	2.447 × 10 <sup>-7</sup>	4.099 × 10 <sup>6</sup>	4.092 × 10 <sup>6</sup>	4.132 × 10 <sup>-4</sup>	1.691 × 10 <sup>3</sup>

**Summation = 9.294 × 10<sup>3</sup>**

4.1.- Other numerical results obtained with the computer are shown in the Table (3)

**Table (3)**  
**Other numerical results**

Values used in the computer program

$L = 0.0422 \text{ cm}^3 \text{ MEA/cm}^2 \text{ s}$ ,  $\varepsilon = 0.723$ , “a” =  $0.668 \text{ cm}^2/\text{cm}^3$ ,  $\text{He} = 40000 \text{ cm}^3 \text{ atm/gmol CO}_2$ ,  
 $z = 2$ ,  $P_{\text{operation}} = 0.771 \text{ atm}$ ,  $k_2 = 10200 \frac{L}{\text{gmol s}}$  at  $30^\circ\text{C}$ ,  $T_{\text{operation}} = 28^\circ\text{C}$

molar fractions of CO <sub>2</sub> between the ends	partial pressures of CO <sub>2</sub>	Concentration of the free amine [B] (unreacted at the selected point) [2]	enhancement factor E or reaction factor	Individual mass transfer coefficient with chemical reaction on the liquid side $k_L R = k_L E$
	(atm)	(gmol MEA / L solution)		cm / s
$y_{\text{bottom}} = 0.1527$	0.118	0.376	4.027	0.064
0.1462	0.113	0.809	5.006	0.08
0.1396	0.108	1.241	5.666	0.091
0.1330	0.103	1.667	6.175	0.099
0.1264	0.097	2.087	6.596	0.106
$y_{\text{top}} = 0.1198$	0.092	$[B^0] = 2.5$	6.959	0.111

Hatta's number $\sqrt{M}$	The reaction is pseudo-first order $\sqrt{D_{A \text{ CO}_2} k_2 [B]} < \frac{1}{2} k_L \left( 1 + \frac{D_{B \text{ MEA}} [B]}{z D_{A \text{ CO}_2} [A^*]} \right)$		Pseudo-first-order reaction comprised in the liquid film $E_i > 5 \sqrt{M}$	
12.783	0.205	0.34	42.518	63.915
18.742	0.3	0.754	94.216	93.711
23.219	0.372	1.207	150.827	116.094
26.909	0.431	1.698	212.223	134.545
30.105	0.482	2.233	279.172	150.523
32.951	0.527	2.821	352.614	164.753

$R_A$	$[A^*]$ in the selected points
$\frac{\text{gmol absorbed of CO}_2}{\text{cm}^2 \text{ s}}$	$\frac{\text{gmol of CO}_2}{L_{\text{solution}}}$
$1.841 \times 10^{-7}$	$2.943 \times 10^{-3}$
$2.176 \times 10^{-7}$	$2.818 \times 10^{-3}$
$2.339 \times 10^{-7}$	$2.691 \times 10^{-3}$
$2.419 \times 10^{-7}$	$2.564 \times 10^{-3}$
$2.44 \times 10^{-7}$	$2.436 \times 10^{-3}$
$2.447 \times 10^{-7}$	$2.309 \times 10^{-3}$



### 4.2.- Graphic results

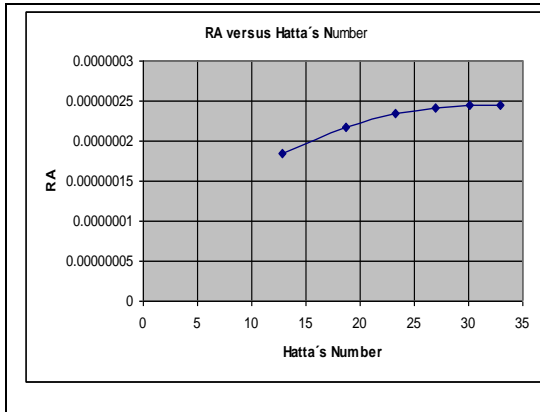


Fig. (7)

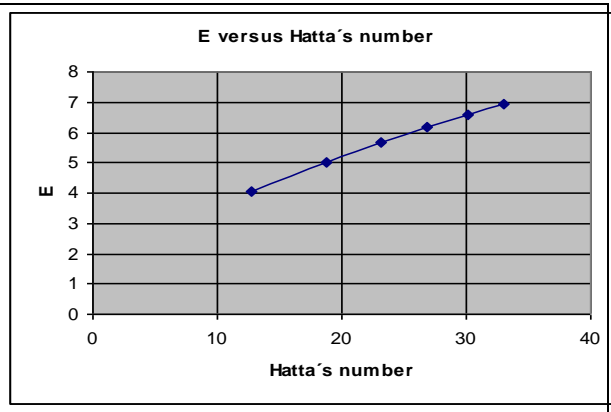


Fig. (8)

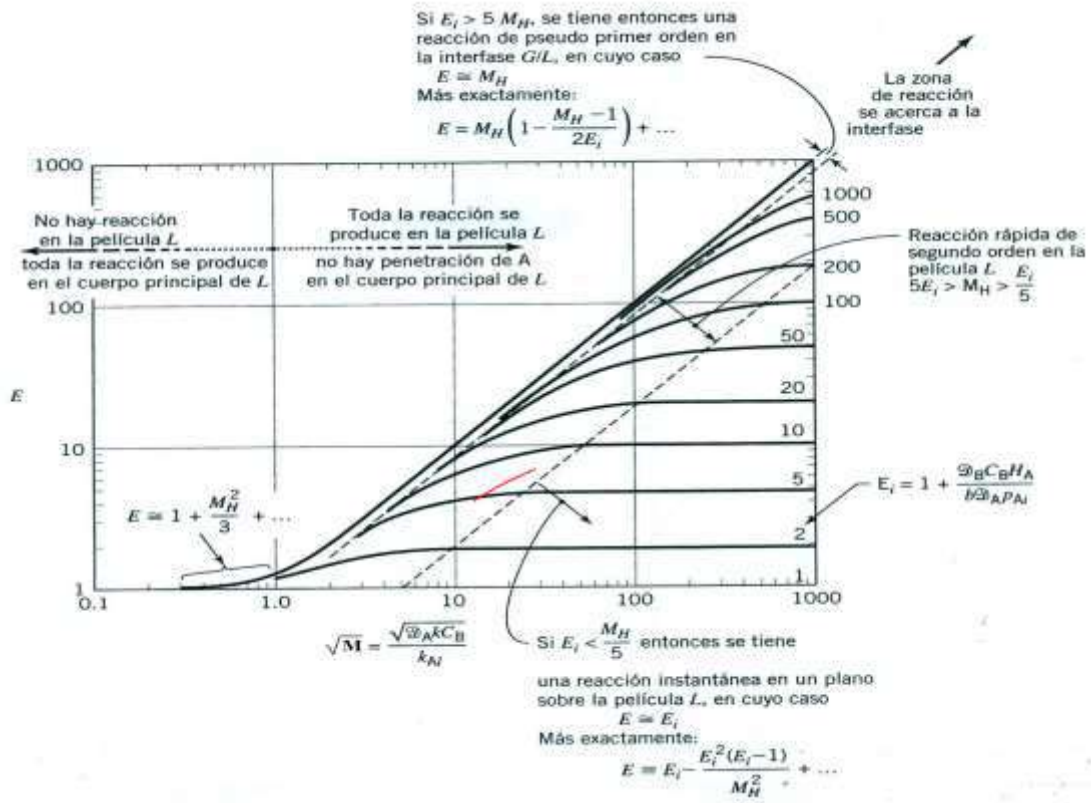


Fig. (9)

### 5.- CONCLUSIONS

The results of subsection 4 were obtained with the experimental conditions of operation of the absorption tower indicated in Table (1), can be summarized as follows:

**5.1** For the values reported in the first column of the Table (2) the following condition is met in the seventh column  $\sqrt{M} < \frac{1}{2}E_i$ ; then  $\sqrt{D_A CO_2 k_2 [B]} < \frac{1}{2}k_L \left( 1 + \frac{D_B MEA [B]}{z D_A CO_2 [A^*]} \right)$  and E is something close to the limiting diagonal  $E = \sqrt{M}$  and subsequent procedures are on a pseudo-first-order reaction, this is, the expression  $\sqrt{M} < \frac{1}{2}E_i$  suggests a shift to the left of Fig. (9) where the region of the pseudo-first-order reactions near the diagonal  $E = \sqrt{M}$  is located, where in this region the concentration of the amine [B] is higher compared to the concentration of the CO<sub>2</sub>, the amine does not become significantly impoverished in the film of liquid and is reduced to a pseudo-first-order reaction.

**5.2** The reaction is given in the film of the liquid according to the experimental profile in red of Fig. (8) shown in Fig. (9),  $E \text{ Vs. } \sqrt{M}$ , since it is located within an amplitude of 1 to 25 of the Hatta number of Fig. (9) and also the following condition is fulfilled  $5\sqrt{M} < E_i$  with values reported in Table (2), that is, this expression suggests a shift to the left of Fig. (9) where the region of the reactions that occur in the liquid film, close to the diagonal, is located  $E = \sqrt{M}$ .

**5.3** In section 3.3 an analysis was made to determine if the reaction is reversible under the operating conditions of Table (1). It was proved that the top and in the bottom of the column the reaction is not reversible, since the back pressure at the interface can be neglected since it is even lower than the respective partial pressures of CO<sub>2</sub> in the gas phase  $p_{CO_2} > p_{iinterphase}$ .

**5.4** The analysis of Fig. (7) indicates that in the dome of the column the rapidity of absorption in the presence of chemical reaction is high and that it is accompanied by a mechanism by small diffusion in comparison with the reaction, here it will be rapidly consumed CO<sub>2</sub> that is being absorbed, where the reaction is controlled by diffusion, but as the number of Hatta decreases along the column, the speed of absorption decreases and the diffusive mechanism begins to increase, affecting the reaction mechanism.

**5.5** The results obtained by the students served to formulate correlations when the tower was manipulated to other experimental flows. During the experiments, the teachers observed the abilities of the students in the fields of skills, knowledge and attitudes. During the development of the practice the knowledge of mass transfer and engineering of the students was used, the tools were used to manipulate the equipment, computer programs were developed, the necessary controls were taken to work in teams, were obtained results and reports are presented. with ingeniously reliable results.

## 6.- NOMENCLATURE

[A<sub>0</sub>] = Concentration of CO<sub>2</sub> in the bulk of the liquid phase: gmol CO<sub>2</sub> /L solution

[A] = Concentration of CO<sub>2</sub> in the liquid phase: gmol CO<sub>2</sub> / L solution

[A°] = Initial CO<sub>2</sub> concentration: gmol CO<sub>2</sub> / L solution

**a** = Effective interfacial area per unit of packed volume: cm<sup>2</sup>/cm<sup>3</sup>

A<sub>column</sub> = Internal area of the column: cm<sup>2</sup>

Ae = Concentration of CO<sub>2</sub> in equilibrium in the bulk of the liquid phase: gmol CO<sub>2</sub> / L

**at** = Area of total packing surface per unit of packed volume: cm<sup>2</sup>/cm<sup>3</sup>

[A\*] = Interfacial concentration of CO<sub>2</sub> in the film model: gmol CO<sub>2</sub> / L solution

[B<sub>0</sub>] = Bulk concentration in liquid phase: gmol MEA /L solution

[B°] = Initial concentration of MEA: gmol MEA /L solution

**D** = Diffusion coefficient: cm<sup>2</sup>/s

- E** = Enhancement factor  
**E<sub>i</sub>** = Enhancement factor for an infinitely fast reaction  
**E<sub>1</sub>** = Enhancement factor given by equation (26)  
**G** = Mass velocity of the gas stream: g/s cm<sup>2</sup>  
**H** = Height of the absorption column: cm  
**H<sub>e</sub>** = Constant of Henry: cm<sup>3</sup> atm / gmol CO<sub>2</sub>  
**j<sub>A</sub>** = Flux diffusive: gmol A/ s cm<sup>2</sup>  
**k<sub>1</sub>** = First order reaction rate constant: 1/s  
**k<sub>2</sub>** = Second order reaction rate constant: L / gmol s  
**k<sub>G</sub>a** = Individual and temporary volumetric coefficient on the side of the gas phase: gmolCO<sub>2</sub> /s cm<sup>3</sup> atm  
**k<sub>L</sub>a** = Individual and temporary volumetric coefficient physical absorption on the side of the liquid phase: 1/ s  
**k<sub>L</sub>R<sub>a</sub>** = Individual and temporary volumetric coefficient chemical absorption on the side of the liquid phase: 1/s  
**k<sub>L</sub>R** = **k<sub>L</sub> E**  
**L** = Mass velocity of the liquid stream: g/s cm<sup>2</sup>  
 $\sqrt{M}$  = Hatta number  
**p** = Pressure: atm  
**p<sub>i</sub>** = Interfacial pressure on the side of the gas phase: atm  
**r** = Reaction speed: (cm<sup>3</sup>/gmol)<sup>-1+n</sup> /s  
**R<sub>A</sub>** = Absorption speed with chemical reaction through the interface: gmol A/ s cm<sup>2</sup>  
**S** = Interfacial surface in the film model: cm<sup>2</sup>  
**t** = Time = s  
**x** = Abscissa in the model of the film, arbitrary position in the absorption column: cm  
**z** = Stoichiometric reaction factor between carbon dioxide and monoethanolamine with a value of 2  
**ε** = Fraction of gaps between the packaging of the absorption column  
**δ** = Thickness of difusión film: cm  
**σ<sub>L</sub>** = Surface-tension of liquid: dynas / cm  
**σ<sub>C</sub>** = The critical surfase-tension: dynas / cm  
**ρ<sub>G</sub>** = Density of the gas phase: gr/cm<sup>3</sup>  
**ρ<sub>L</sub>** = Density of the liquid phase: gr/cm<sup>3</sup>

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