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CHARACTERISATION OF MELLAPAK 750Y STRUCTURED PACKING DETERMINING THE EFFECTIVE MASS TRANSFER AREA

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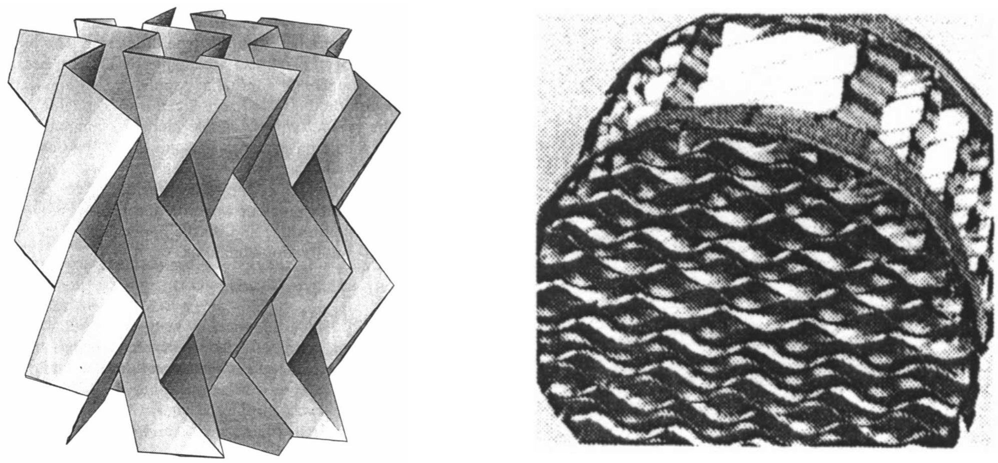
ABSTRACT. The effective mass transfer area of a Mellapak 750 Y structured packing was measured in a bench- scale plant with a column having an internal diameter of 100mm, and a packing height of 518 mm, using a broad range of gas and liquid flow rates. The absorption of carbon dioxide into natrium hydroxide aqueous solutions of 0.5 and 1.0 mol/L has been employed as test reaction. The validity of data obtained was tested by checking the two conditions of fast pseudo first order irreversible reaction. The data have been correlated by a criterial equation giving the ratio between the effective and the geometric areas versus the Reynolds number of the liquid phase. The coefficients of the equation have been identified by regression.

Keywords: absorption rate, absorption column, chemical method, criterial equation.

INTRODUCTION

Increased attention has been devoted in the last few years to optimize the absorption process. This was partly due to the severity of the legislation imposed in industrial countries on the prevention of air and water pollution [1]. The conventional beds of random packing caused difficulties in large diameter industrial separation columns. A frequent difficulty has been to attain uniform distribution of the liquid over the entire cross section and to assure that the packing was adequately wetted. The risk of malldistribution also existed in the region on packing close to the wall. Therefore, researchers and manufacturers have studied and developed new types of column interiors. Among these interiors, corrugated packings of the regular type, also called *structured packing,* have received the greatest attention owing to their favorable performance [2,3]. It is recognized that structured packing makes possible reduction in exergy consumption by minimizing pressure drop per theoretical stage [3,4]. Structured packing can be made of plastic or metallic materials, depending on the application. They are made of corrugated sheets arranged in parallel, successive layers having an opposite angle of corrugation as shown in Figure 1. Flow channels resulting from this arrangement are inclined at an angle of 60 or 45 degrees to the horizontal. The particular from of the packings makes it possible to obtain a high geometric specific area, from 150 m^2/m^3 with Mellapak 150 Y to 750 m^2/m^3 Mellapak 750 Y.



a. b.

Figure 1. Structured packing of Mellapak 750 Y type. a- corrugated sheets, b- element of structured packing.

The present paper is devoted to the effective mass transfer area measurement of the Mellapak 750Y packing. The *effective* mass transfer area (a_e) is not identical neither to the *geometric* area (a) nor to the *wetted* area of the packing (a_w). The measurement of the specific geometric area of packing is straight forward but it is not a design parameter. The wetted area is that part of geometric area over which there is a liquid film. It depends on the surface tension interaction between the liquid and the solid packing, and can be measured by the dye technique. The effective mass transfer area may differ from the wetted area because of packets of almost stagnant liquid formed in contact points of packings. This liquid can account for the large wetted area but is practically useless for absorption because it comes quickly to equilibrium with the gas.

The effective mass transfer area is determined by chemical methods using a gas -liquid process as " model reaction" of known kinetics. The sulphite method, employing the oxidation of $NaSO_3$, has been frequently used as test reaction [5,6,7]. Although there is controversy regarding the reaction order with respect to oxygen and the reproductibility of the reaction kinetics is almost impossible [3,6]. Therefore, the absorption of CO_2 diluted with air into NaOH solutions has been chosen as model reaction in this work.

1. EXPERIMENTAL

The Mellapak structured metal sheet packing has been purchased from Sulzer Brothers Limited (Winterthur, Switerland). The corrugations of the metal sheets were inclined by an angle with respect to the vertical axis. For the Mellapak Y types this angle is always of 45^0. The sheets are arranged vertically and parallel to each other (Figure 1). These corrugations define straight inclined channels of triangular cross section through which the gas flows. The liquid flows down the corrugated sheets approximately in countercurrent fashion to the gas. The Mellapak type used in this study was 750 Y, with a geometric specific area of 750 m^2/m^3 and a void fraction of 0.95. Measurements were also carried out with column packed with Raschig rings of 10 x8 x10 mm, made of glass , with the geometric area of 570 m^2/m^3 and a void fraction of 0.8. The flow chart of the bench- scale plant used for the absorption rate and pressure drop measurements is reproduced in the Fig 2.

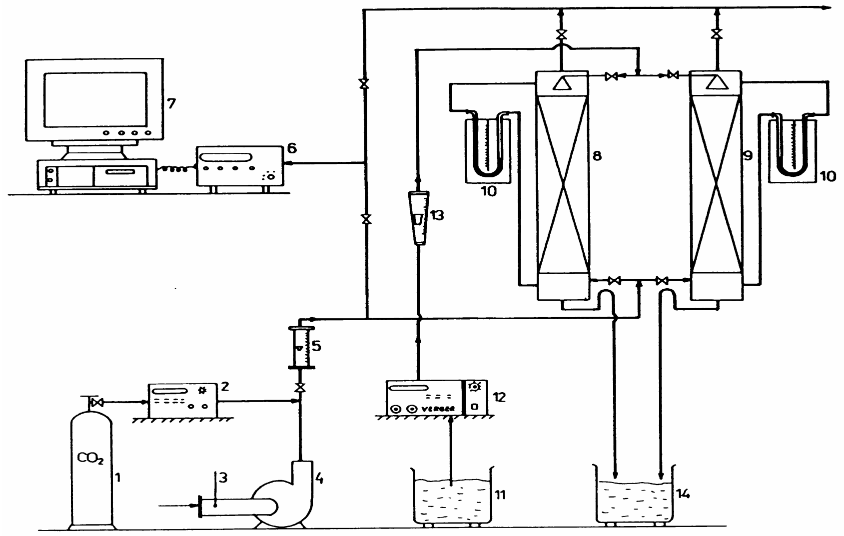


Figure 2. The experimental bench-scale plant
1-carbon dioxide cylinder, 2- carbon dioxide mass-flow meter, 3-air temperature controller, 4- air blower, 5- rotameter, 6- gas analyzer , 7- IBM compatible personal computer, 8/9- absorption columns, 10- manometer (mm WG), 11/14- solution tanks, 12- liquid pump, 13- liquid rotameter.

The first absorption column was equipped with a bed of 4.3175 liters of conventional packing. The second column contained 4.0663 liters of Mellapak 750 Y structured packing. To simulate the carbon dioxide absorption into the aqueous

NaOH solutions, three types of gas mixtures containing 5 %, 8 %, and 10 % vol. CO_2 have been used. The gas mixtures have been prepared from purified air and CO_2 of 99.99 purity from the cylinder. The aqueous NaOH solutions containing 0.5 , and 1.0 mol/L have been prepared from distilled water and NaOH of 99.99 purity from Merck GmbH. The solution has been analyzed by pH metric titration. The inlet and the outlet CO_2 concentrations in the gas mixture have been determined by BINOS 120 gas analyzer. The absorption rate has been calculated from the measured inlet (Y^0_{CO2}) and outlet (Y_{CO2}) concentrations of the CO_2 in the gas by the equation (1):

$$\text{Vab}= KV_G\left(\frac{Y^0{}_{CO2} - Y_{CO2}}{1-Y_{CO2}}\right) \text{ kmol/m}^3\text{s} \qquad (1)$$

where : K = 10.0577 for the Mellapak , and K = 9.4725 for the Raschig rings.

The investigated systems and the variable factors (type of packing included) are listed in the Table 1.

Table 1.

The experimental conditions (T = 298 K, P= 1 bar)

Packing	Mellapak 750Y	Raschig rings
Column diameter, m	0.100	0.100
Height of the bed, m	0.518	0.550
Packing volume, L	4.0663	4.3175
Nominal size of the packing , mm	-	10 x 8 x 10
Equivalent diameter, mm	0.400	2.105
Void fraction of the bed	0.95	0.80
Geometric surface area, m^2/m^3	750	570
Concentration of NaOH solution, mol/L	0.50 ; 1.00	
CO_2 mole fraction in the gas mixture	0.05 ; 0.08 ; 0.10	
Gas flow rate, m^3/h	3.0 ; 5.0 ; 10.0	
Liquid flow rate, L/h	100 ; 120 ; 160 ; 200 ; 250.	

By combining the five variable factors a number of 240 pairs of input – output concentrations had to be measured in order to determine the corresponding absorption rates.

2. RESULTS

The tables 2 and 3 presented in this paper are only two of the sixteen tables containing all measured and calculated data.

Table 2.

Measured concentrations and calculated absorption rates in the two columns at C^0_{NaOH} = 0.5 mol/L, and V_G= 10 m^3/h.

No	Y^0_{CO2}	V_L, L/h	Mellapak 750 Y		Raschig rings	
			Y_{CO2}	$V_{ab,}\,10^4$ kmol/m^{3}s	Y_{CO2}	$V_{ab,}\,10^4$ kmol/m^{3}s
1	0.05	100	0.035	4.343	0.035	4.093
2	0.05	120	0.034	4.627	0.033	4.629

3	0.05	160	0.031	5.478	0.031	5.163
4	0.05	200	0.028	6.323	0.027	6.224
5	0.05	250	0.025	7.163	0.024	7.015
6	0.08	100	0.059	6.235	0.059	5.876
7	0.08	120	0.058	6.525	0.058	6.149
8	0.08	160	0.056	7.103	0.055	6.966
9	0.08	200	0.050	8.822	0.049	8.583
10	0.08	250	0.046	9.957	0.045	9.653
11	0.10	100	0.075	7.551	0.073	7.669
12	0.10	120	0.074	7.844	0.072	7.945
13	0.10	160	0.071	8.721	0.068	9.041
14	0.10	200	0.066	10.168	0.062	10.667
15	0.10	250	0.060	11.888	0.058	11.740

Table 3.

Measured concentrations and calculated absorption rates in the two columns at C^0_{NaOH} = 1.0 mol/L, and V_G= 10 m^3/h.

No	Y^0_{CO2}	$V_{L,}$ L/h	Mellapak 750 Y		Raschig rings	
			Y_{CO2}	$V_{ab,\ 10}{}^4$ kmol/m^{3}s	Y_{CO2}	$V_{ab,\ 10}{}^4$ kmol/m^{3}s
1	0.05	100	0.031	5.478	0.030	5.429
2	0.05	120	0.030	5.761	0.029	5.695
3.	0.05	160	0.027	6.604	0.026	6.488
4	0.05	200	0.024	7.443	0.022	7.538
5	0.05	250	0.022	7.199	0.020	8.061
6	0.08	100	0.050	8.823	0.050	8.315
7	0.08	120	0.049	9.107	0.049	8.583
8	0.08	160	0.047	9.675	0.046	9.384
9	0.08	200	0.042	11.082	0.041	10.707
10	0.08	250	0.040	11.642	0.039	11.244
11	0.10	100	0.065	10.458	0.066	9.585
12	0.10	120	0.064	10.746	0.064	10.127
13	0.10	160	0.060	11.889	0.059	11.473
14	0.10	200	0.054	13.586	0.052	13.332
15	0.10	250	0.049	14.983	0.047	14.644

As one can see from the two tables, the absorption rate in the column equipped with Mellapak 750Y is equal and frequently superior to that in the column with Raschig rings. To achieve the same and even a superior absorption rate with a pressure drop twenty folds lower [4] is obviously an important economic advantage of the structured packing. The next section is devoted to the effective mass transfer area determining.

3. EFFECTIVE MASS TRANSFER AREA

The absorption process carried out in the two experimental columns was accompanied by an irreversible second order reaction between the dissolved CO_2 and the NaOH in solution:

$$CO_2 + 2\,HO^- = CO_3^{\,2-} + H_2O \tag{2}$$

The concentration profiles of the two reactants in the liquid film are described by the differential equations (3) and (4):

$$D_{CO2}\frac{d^2C_{CO2}}{dx^2} + k_2 C_{CO2} C_{HO-} = 0 \tag{3}$$

$$D_{HO-}\frac{d^2C_{HO-}}{dx^2} + 2k_2 C_{CO2} C_{HO-} = 0 \tag{4}$$

with: $x = 0$; $C_{CO2} = C^i_{CO2}$; $\frac{dC_{HO-}}{dx} = 0$

$$x = \delta \;;\; C_{CO2} = C^0_{CO2} \;;\; C_{HO-} = C^0_{HO-} \tag{5}$$

The analytical solution of the system (3) – (5) leads to the enhancement factor concept (E). This solution is available only if the reaction is considered to be pseudo -first order, i.e. the concentration of NaOH is udepleted in the liquid film [8,9.,10]: $C_{HO-} = C^0_{HO-}$. The solution is of the implicite form:

$$E = \frac{Ha\left(1 - \frac{E-1}{\beta}\right)}{\tanh\left[Ha\left(1 - \frac{E-1}{\beta}\right)^{1/2}\right]} \tag{6}$$

where: $$Ha = \frac{\left(k_2 C^0{}_{HO-} D_{CO2}\right)^{1/2}}{k_L{}^0} \tag{7}$$

$$\beta = \frac{D_{HO-} C^0{}_{HO-}}{2 D_{CO2} C^i{}_{CO2}} \tag{8}$$

$$\alpha = \frac{C^0{}_{CO2}}{C^i{}_{CO2}} = 0 \tag{9}$$

In the *fast reaction regim*, defined by Ha > 5 , the enhancement factor equals the Hatta number and the absorption rate becomes:

$$V_{ab} = a_e C^i{}_{CO2}\left(k_2 C^0{}_{HO-} D_{CO2}\right)^{1/2} \qquad (10)$$

with: $$E = Ha > 5 \qquad (11)$$

The condition (11) is necessary but not sufficient because at Ha >5 the reaction may become spontaneous, too [10]. Therefore, a second condition must be fulfilled [9]:

$$\frac{Ha}{1+\beta} < 0.5 \qquad (12)$$

By representing the experimental absorption rate versus X = $C^i{}_{CO2}\left(k_2 C^0{}_{CO2} D_{CO2}\right)^{1/2}$, the effective mass transfer area can be obtained , as a slope of the straight line passing through the origin (Figs. 2 and 3).

Table 4.

The X coordinate of Figs. 2 and 4. X = $C^i{}_{CO2}\left(k_2 C^0{}_{CO2} D_{CO2}\right)^{1/2}$ x10^6, kmol/m^{2}s

C^0_{HO-} / Y^0_{CO2}	0.05	0.08	0.10
0.5	4.4180	7.0690	8.8360
1.0	5.7686	9.2995	11.5373

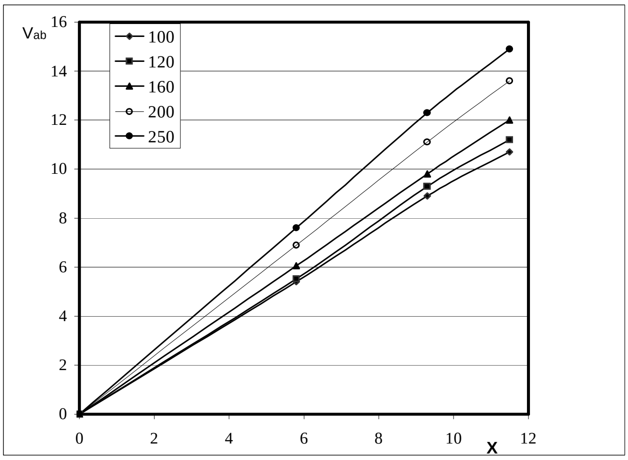


Figure 3. Absorption rate (10^4 kmol/m^{3}s) versus X, at C^0_{HO-}=1.0 mol/L, V_G=10 m^3/h, T = 298 K, Mellapak 750Y (V_L in L/h as parameter)

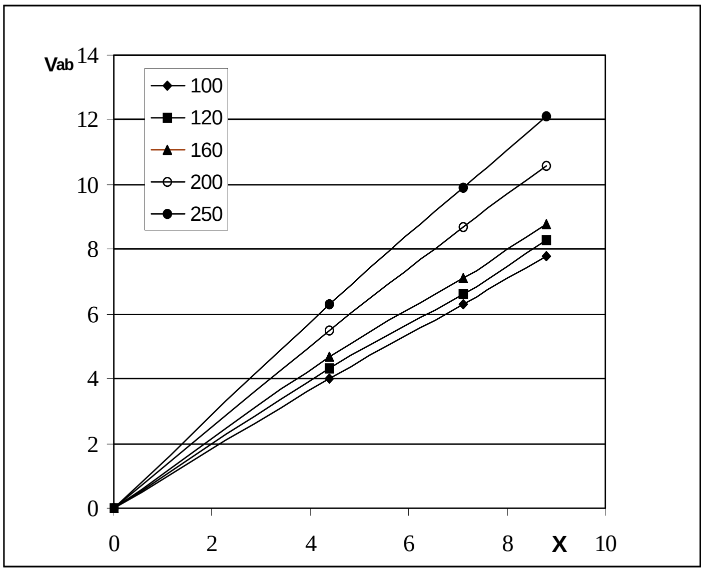


Figure 4. Absorption rate (10^4 kmol/m^{3}s) versus X, at C^0_{HO-}=0.5 mol/L, V_G=10 m^3/h, T = 298 K, Mellapak 750Y (V_L in L/h as parameter)

The numerical values of the determined effective area from Figs. 3 and 4 are gathered in the Table 5.

Table 5.
Effective mass transfer area (a_e, m^2/m^3) of the Mellapak 750Y packing

C^0_{HO-} / V_L, L/h	100	120	160	200	250
0.5 mol/L	90.589	95.257	107.722	127.726	145.840
1.0 mol/L	93.504	97.001	107.199	122.996	135.326
Average	92.046	96.127	107.460	125.361	140.583

4. DATA VALIDATION AND CORRELATION

The values of the effective area in Table 5, determined by the equation (10) are valid only if the conditions (11) and (12) have been satisfied during the experiments. The Tables 6 and 7 present the numerical values of Hatta and $Ha/_{1+\beta}$, respectively.

Table 6.
Hatta number for the experimental conditions(T = 298 K, and k^0_L = 6.09 10^{-5} m/s)

C^0_{HO-}, mol/L	0.10	0.50	1.0	2.0
k_2 10^4, L/mol s	0.838764	1.019060	1.278497	1.904145
D_{CO2} 10^9, m^2/s	1.9627	1.8727	1.7479	1.6010
Ha	21.062	50.707	77.600	128.137

Table 7.

The ratio $Ha/(1+\beta)$ for the experimental conditions.

Y^0_{CO2} / C^0_{HO-}	0.10	0.50	1.00	2.00
0.05	0.3817	0.1644	0.1072	0.0650
0.08	**0.6042**	0.2623	0.1717	0.1040
0.10	**0.7498**	0.3716	0.2146	0.1293

The necessary equations for the calculations of the parameters included in the relations (11) and (12) are listed in the **Appendix** [9,11-14]. As one can see from Tables 6 and 7, both conditions have been satisfied during the measurements.

Another way to validate the numerical values of the effective area obtained in this work could be the comparison with the existing data for similar packings. Unfortunately, such data for Mellapak 750 Y are lacking. The equation of Onda et all., cited by Danckwerts [9] , predicts the wetted area of the conventional packings while the equation of Rizzuti and Brucato, cited by De Brito et all. [3], was established for effective area but also for random packed beds.

The data in Table 5 obtained in this work have been correlated by the criterial equation of the form:

$$\frac{a_e}{a} = 0.1245\left(\frac{\rho_L d_p v_L}{\mu_L}\right)^{0.4} \qquad (13)$$

where:

$$d_p = \frac{6(1-\varepsilon)}{a} \qquad (14)$$

The constant and the exponent of the equation (13) have been identified by regression.

5. CONCLUSIONS

The effective mass transfer area of a Mellapak 750 Y structured packing and of 10 x 8 x10 glass Raschig rings has been determined by measuring. The absorption rates in two columns under identical operating conditions. The absorption of carbon dioxide diluted with air into aqueous NaOH solutions was employed as model reaction of known kinetics.

The new determined values for Mellapak 750Y have been correlated by a criterial equation. New measurements have to be done in broader intervals of fluid flow rates, at larger scale.

NOTATION

a , geometric specific area of the packing, m^2/m^3;

a_e, effective mass transfer area, m^2/m^3;

a_w, wetted area of the packing, m^2/m^3;

$C_{CO2,}$ C_{HO-}, molar concentration in the liquid film of the carbon dioxide and natrium hydroxide , respectively, mol/L;

C^i_{CO2}, concentration of dissolved CO_2 at the interface, mol/L;

C^0_{CO2}, C^0_{HO-} , concentration in the liquid bulk of the CO_2 and HO^- respectively, mol/L;

d_p, equivalent diameter of the packing, m;

$D_{CO2,}$ D_{HO-}, diffusivity in the liquid phase of CO_2 and HO^- , m^2/s;

E , enhancement facor;

Ha, Hatta number;

H, Henry constant, mol/L bar;

H_0, Henry constant of CO_2 in water , mol/L bar;

K, constant in the equation (1);

k_2, second- order reaction rate constant, mol/L s;

k^0_L, physical mass transfer coefficient of CO_2 in the liquid phase , m/s;

P, total pressure, bar;

p_{CO2}, partial pressure of CO_2, bar;

T, temperature, K;

tanh, hyperbolic tangent;

V_{ab}, absorption rate, $kmol/m^3s$;

V_G, gas flow rate , m^3/s;

V_L, liquid flow rate , m^3/s;

v_L, liquid rate , m^3/m^2s;

X , coordinate in the figs. 3 and 4, $kmol/m^2s$;

α , the ratio $C^0_{CO2}/C^i_{CO2;}$

β , non dimensional group defined by the equation (8);

δ , liquid film thickness, m;

ε , void fraction of the packing bed;

μ_{HO_2} , μ_L , viscosity of the water and the solution, respectively, Pa s;

ρ_L , liquid density, kg/m^3.

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APPENDIX

The concentration of dissolved CO_2 at the interface can be predicted by the system (A_1-A_3):

$$C^{i}{}_{CO2} = H.p_{CO2} \qquad (A_1)$$

$$\log\frac{H}{H_0} = -0.138C^{0}{}_{NaOH} \qquad (A_2)$$

$$\log H_0 = \frac{1140}{T} - 5.30 \qquad (A_3)$$

The CO_2 diffusivity in pure water depends on the temperature as follows:

$$\log D^{0}{}_{CO2} = -8.1764 + \frac{712.5}{T} - \frac{2.591x10^5}{T^2} \qquad (A_4)$$

while the diffusivity of the CO_2 in the NaOH aqueous solution was calculated by the realtion:

$$D_{CO2} = D^{0}{}_{CO2}\left(\frac{\mu_{H_2O}}{\mu_L}\right)^{0.637} \qquad (A_5)$$

The second -order reaction constant k_2 depends both on the temperature and on the ionic strength in a non- linear manner:

$$\log k_2 = 11.895 - \frac{2382}{T} + 0.221C^{0}{}_{NaOH} - 0.016\left(C^{0}{}_{NaOH}\right)^2 \qquad (A_6)$$

The physical mass transfer coefficient (k^0_L) has been evaluated by the equation of Onda et all [9]:

$$\frac{k^0{}_L}{aD_{CO2}} = 0.0051(ad_p)^{0.4}\left(\frac{v_L\rho_L}{a\mu_L}\right)^{4/3}\left(\frac{av^2{}_L}{g}\right)^{-1/3}\left(\frac{\mu_L}{\rho_L D_{CO2}}\right)^{1/2} \quad (A_7)$$

The ratio D_{HO^-}/ D_{CO2} is generally between 1.67 and 2.1. A value of 1.70 has been adopted.