Effect of Column Variables on the Effective Mass Transfer Area and Efficiency in Packed Column

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ABSTRACT

Carbon dioxide, a component gas in biogas, not only lowers its calorific value but is a greenhouse gas contributing to global warming. To increase the calorific value, the raw gas is upgraded by sequestering $\text{CO}_2$ in a packed absorption column using a reactive solvent. This study investigates the effect of the effective mass transfer area $a_e$, on the column efficiency considering a select set of column variables. These variables are the gas and solvent superficial velocities, solvent concentration and $\text{CO}_2$ concentration in the raw gas. The column was randomly packed using glass spheres of equal diameter. Experimental results showed that the column efficiency is a function of the effective area $a_e$, which is greatly influenced by the solvent superficial velocity and the solvent concentration while carbon dioxide concentration in the gas feed has least effect. From these findings, high column efficiency is attained at high ratios of solvent to gas superficial velocities due to the increased value of the effective area, created by the increase in turbulence in the liquid phase.

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INTRODUCTION

The current world insatiable energy demand is caused by the current rapid economic growth especially in the developing world with the demand not met by the dwindling fossils fuel reserves. This has given rise to the development of different energy technologies like hydropower, solar energy, wind energy, geothermal and biogas [1].

Apart from it being used as a feedstock in the production of chemicals, hydrogen and syngas, biogas is a significant source of energy which is produced from methanation of biomass through the process of anaerobic digestion [2]. The main gasses in biogas comprise of 60 – 70% combustible CH₄ and 30 – 40% noncombustible CO₂ along with traces of oxygen (0 – 1%), nitrogen (< 1%), siloxane (0 – 0.02%), halogenated hydrocarbons (< 0.6%), carbon monoxide (< 0.6%), hydrogen sulfide (0.005 – 2%) water vapor (5 – 10%) and hydrogen [3]. The raw gas is upgraded to biomethane with high methane content by sequestration of CO₂, a recalcitrant gas that decrease the overall calorific value biogas, and all the other constituent gasses to meet the specification of the Wobbe Index [2,4]. Biomethane constitutes 95 – 99% CH₄ and 1 – 5% CO₂.

Upgrading the biogas is achieved by, among others, cryogenic and membrane separations, pressure swing adsorption, carbon dioxide fixation by chemical or biological methods and CO₂ absorption in a packed column [4]. In the column, sequestration of CO₂ is by a solvent that runs co- or counter-current to the gas stream over the packing, creating turbulence as the two fluids interact. The choice of the solvent often dictates whether the absorption process is a physical or chemical an absorption based in the reactivity of the solvent and the solute molecules. The solvents include alkaline, amine, ionic solutions, or ammonia. Chemical absorption is a preferred method in upgrading biogas as it completely removes H₂S with a low operating pressure and with a high column efficiency as compared to physical absorption [1].

The use of aqueous NaOH solution in absorption of CO₂ has been studied extensively since the 1940s with focus being mass transfer coefficient, the rate of absorption, film resistance and the general column performance. It is an ionic solvent with a high absorption capacity producing NaHCO₃ as the final product of absorption which is very soluble in aqueous solution, readily decomposing to Na₂CO₃, H₂O and CO₂ at low temperatures. However, Na₂CO₃ is thermally stable curtailing regeneration of NaOH solution [5].

In the column, transfer of solute molecules from the gas phase to the liquid phase is facilitated by the effective area for mass transfer \( a_e \) is a fraction of the total wetted area over the packing \( a_w \) [6]. The difference is made up of the dead zones whose magnitude reduces with increase in solvent superficial velocity \( u_x \) in the column. Increasing the velocity increases turbulence in the column a phenomenon that makes the effective area greater than the geometric area \( a_p \) [7,8]. Correlations have shown that the effective area is directly proportional to the density of the solvent \( p_x \), and the gravitational field strength \( g \) and is inversely proportional to the surface tension of the solvent \( \sigma_x \) [9].

This paper investigates the influence if the hydrodynamics of the fluid and its properties of the effective area for mass transfer and its effect on CO₂ removal efficiency \( \eta \).

THEORETICAL FRAMEWORK

Solute-solvent reaction mechanism

The solute molecules are partially transported from the gas phase to the liquid phase, reacting with NaOH in the reaction zone, placed at a distance \( \delta x \) into the liquid film. It reacts with NaOH by first being physically absorbed into the aqueous solution [5].

\[
CO_2(g) \rightarrow CO_2(aq) \quad (1)
\]

At the same time, the aqueous NaOH solution in the film, being a strong alkaline solution, dissociates into sodium and hydroxide ions.
\[ NaOH \rightarrow Na^+ + OH^- \]  

(2)

The aqueous CO\(_2\) then reacts with the hydroxide ions to form bicarbonate and carbonate ions via Eqs. (3 and 4).

\[ CO_2(aq) + OH^-_{(aq)} \rightleftharpoons HCO_3^-_{(aq)} \]  

(3)

\[ HCO_3^-_{(aq)} + OH^-_{(aq)} \rightleftharpoons H_2O(l) + CO_3^{2-}_{(aq)} \]  

(4)

These two reactions are reversible and exothermic in the forward direction and both are characterized by high reaction rates at high pH values and since Eq (4) is instantaneous, Eq (3) is considered to be rate controlling reaction [10].

In the early stages of the absorption process, the alkalinity of the solvent makes reaction in Eq. (4) predominant increasing the concentration of the carbonate ions relative to the bicarbonate ions in the liquid phase [5]. The two reactions rapidly decrease the hydroxide concentration while increasing the concentration of carbonate ions. Initially the net irreversible reaction of the second order is given by Eq. (5) [10].

\[ 2NaOH(aq) + CO_2(g) \rightarrow Na_2CO_3(aq) + H_2O(l) \]  

(5)

However, as the process proceeds, more carbon dioxide molecules are absorbed through the interface leading to the depletion of the hydroxyl ions thus setting the stage for the accumulation of carbonate ions via Eqs. (3 and 4). Going by the Le Chatelier’s principle, an increase in carbonate ions favours the reverse of reaction in Eq (4), leading to a favourable forward reaction in Eq. (3) [5]. The effect of this is a decrease in concentration of bicarbonate and the pH of the solution with the overall absorption process being represented by equation 6.

\[ Na_2CO_3(aq) + CO_2(g) + H_2O(l) \rightarrow 2NaHCO_3(aq) \]  

(6)

At equilibrium, some additional CO\(_2\) may be absorbed to make up for the shortage of physically unabsorbed CO\(_2\) in water during the reaction [5]. If aqueous sodium hydroxide solution is the limiting reactant, then the overall CO\(_2\) absorption can be summarized as reaction in Eq. (7), which is the net reaction of Eqs. (5 and 6).

\[ NaOH(aq) + CO_2(g) \rightarrow NaHCO_3(aq) \]  

(7)

**The Two-film Theory**

The most widely used fundamental mass transfer model used to quantitatively describe CO\(_2\) absorption process over a packed column is the two-film model. This model was proposed by Whitman (1923) and is the simplest theory designed for mass transfer analysis [11]. The model assumes that this gas and liquid film of equal thickness \( \delta x \), exists on either side of the interface between the phases where resistance to mass transfer is localized [12]. A schematic representation of the two films is presented in Figure 1.

**Figure 1: Schematic representation of the two-film at the interface between the phases**

![Schematic representation of the two-film](image-url)
Due to the absence of turbulence in the two films, the flow is considered laminar and the mass transfer of the solute molecules in the films is exclusively by molecular diffusion and as the solute molecules diffuse, the experience resistance in the individual films with the overall resistance being the summation of the two resistances [13, 14, 15].

\[
\frac{1}{K_y} = \frac{1}{k_y} + \frac{k_H}{\beta k_x^0} \quad (8)
\]

Where, \( K_y \) is the overall mass transfer coefficient based on the gas phase, \( k_y \) is the coefficient in the gas film while \( k_x^0 \) is the liquid film mass transfer coefficient for a physical absorption, \( k_H \) is the Henry’s law constant for \( CO_2 \), a constant which is the ratio of the solute’s partial pressure in air to the concentration of the solute in pure water under equilibrium conditions measured at the interface.

\[
k_H \left( \frac{P_a}{C_{Bulk}} \right) \quad (mol/m^3.Pa) \quad (9)
\]

\( \beta \) is the dimensionless enhancement factor for mass transfer, representing the acceleration of the process of diffusion by the chemical reaction between the solute and the solvent molecules it is the ratio of mass transfer in a chemisorption process to that of a purely physical absorption.

\[
\beta = \frac{k_x^0}{k_x^0} \quad (10)
\]

This is a measure of the contribution of the chemical reaction to the transfer of solute molecules across the interface between the phases.

In investigations done on a wetted wall column with a well-defined interfacial area, the gas phase mass transfer resistance has been found to be less than 10% of the overall resistance [14]. The overall resistance can then be assumed to be equal to the resistance in the liquid film.

\[
\frac{1}{K_y} \approx \frac{k_H}{\beta k_x^0} \quad (11)
\]

The reciprocal of this resistance is the overall mass transfer coefficient \( K_y \), for the system [9, 12].

\[
K_y = K_y' \approx \left( \frac{\beta k_x^0}{k_H} \right) \quad (12)
\]

**Mass Transfer Coefficient**

The effective area for mass transfer \( a_e \), is determined based on the chemical absorption method as proposed by Dankworth in 1970 [16]. Absorption of the solute molecules is controlled by the irreversible reaction between the solutes and solvent in Eq (7) and in the evaluation of \( a_e \), two dimensionless numbers are considered, one is the enhancement factor \( \beta \) and the other is the Hatta number \( Ha \), which is the ratio of the rate of reaction to the rate of diffusion through the interface [17].

\[
Ha = \left( \frac{k_x^0[OH^-]D_{CO_2}}{k_x^0} \right) \quad (13)
\]

Here, \( k_1 \) and \([OH^-] \) are the reaction rate constant for the pseudo-first order reaction and the solvent concentration respectively while \( D_{CO_2} \) and \( k_x^0 \) are the diffusivity of \( CO_2 \) molecules in the liquid film and the film’s mass transfer coefficient respectively.

This parameter is used to establish the reaction regime and the position of the reaction zone within the liquid film considering the following conditions.

- If \( Ha \gg 1 \) and \( Ha \gg \left( \frac{(D_{OH})([OH^-]_{Bulk})}{(D_{CO_2})(P_{CO_2})} \right) \), the reaction is instantaneous and the reaction takes place at the interface.

- It \( Ha \gg 1 \) and \( Ha \ll \left( \frac{(D_{OH})([OH^-]_{Bulk})}{(D_{CO_2})(P_{CO_2})} \right) \), the reaction is a fast reaction and the reaction zone is at a distance \( \delta x \) into the liquid film.

Here, \([OH^-]_{Bulk} \) and \( P_{CO_2} \) are the solvent concentration in the liquid bulk and carbon dioxide partial pressure at the interface.

The absorption of \( CO_2 \) molecules by aq \( NaOH \) solution is a moderately fast reaction that is neither instantaneous nor intermediate but fast enough to justify exclusion of the influence of
physical absorption in the analysis of the transfer process [18]. Depending on the theoretical models used in the reaction, the Hatta number for the system lies in the region between 2 and infinity for infinite enhancement $\beta^\infty$ [19, 20].

$$2 < Ha \ll \beta^\infty \quad (14)$$

It has been established that the $\beta$, is related to $Ha$ by equation 15 [18]

$$\beta = \left( \frac{Ha}{\tanh (Ha)} \right) \quad (15)$$

The Hatta number for this system is 8 [19], making the two parameters approximately equal.

$$\beta \approx Ha \quad (16)$$

The enhancement factor is then calculated using Eq. (17).

$$\beta = \left( \sqrt{\frac{k_1[OH^-]D_{CO_2}}{k_2}} \right) \quad (17)$$

The apparent gas phase mass transfer coefficient $K_y'$, is then evaluated using Eq. (18).

$$K_y' = \left( \frac{gk_2}{k_H} \right) = \left( \frac{k_2}{k_H} \cdot \sqrt{\frac{k_1[OH^-]D_{CO_2x}}{k_2}} \right) = \left( \frac{k_1[OH^-]D_{CO_2x}}{k_H} \right) \quad (18)$$

**Evaluation of the effective area**

The basis of this evaluation is the mass flux and material balance of carbon dioxide over an elemental volume in the packed section of the column [21]. If mass is conserved, the difference in mass flux in the gas stream $G_y$, entering and that leaving is equal up to the mass flux of the solute molecules across the interface between the phases which is absorbed by the solvent stream $L$.

$$\frac{(CO_2 \text{ released by the gas stream})}{(CO_2 \text{ absorbed by the liquid stream})} =$$

$$G(y+dy) - Gy = LP(K_ya_e)(y - y')Sdz \quad (19)$$

$$-\left( \frac{G}{L} \right)dy = P(K_ya_e)(y - y')Sdz$$

$$dz = -\left( \frac{\frac{G}{LPS(K_ya_e)}}{(y-y^*)} \right) \quad (20)$$

Where, $P, y, K_y$ and $a_e$ are the operating pressure, $CO_2$ mole fraction, the overall mass transfer coefficient, and the effective area for mass transfer respectively. The equation is integrated over the following boundary conditions:

At $z= 0, y = y_a$ and at $z= z_T, y = y_b$

$$z_T = \int_0^{z_T} dz = -\left( \frac{G}{LPS(K_ya_e)} \right) \int_{y_a}^{y_b} \frac{dy}{(x-x')} \quad (21)$$

The absorption process is accompanied by a fast reaction with a large enhancement factor $\beta$, the reaction zone is then shifted towards the interface between the phases, making the solute concentration at the interface negligible ($y^* \approx 0$).

$$Z = \int_0^{z_T} dz = -\left( \frac{G}{LPS(K_ya_e)} \right) \int_{y_a}^{y_b} \ln \frac{y_b}{y_a} = -\left( \frac{G}{LPS(K_ya_e)} \right) \ln \frac{y_b}{y_a} \quad (22)$$

And for a unit volume of solvent operating at 1 atmosphere,

$$K_ya_e = \left( \frac{G}{ZRTS} \right) \ln \left( \frac{y_a}{y_b} \right) = \frac{u_yS}{ZRTS} \ln \left( \frac{y_a}{y_b} \right) \quad (23)$$

Where $V, Z$ are the gas molar flow rate and the height of the bed respectively while $y_a$ and $y_b$ the mole fraction of the solute in the gas stream to and from the column respectively. On re-arrangement,

$$a_e = \left( \frac{u_y}{ZRTK_y} \right) \ln \left( \frac{y_a}{y_b} \right) = \left( \frac{u_y}{ZRTK_y} \right) \ln \left( \frac{y_a}{y_b} \right) \quad (24)$$

Where, $u_y$ is the gas superficial velocity. This gives the effective area for mass transfer over the packing surface. The equation is modified to evaluate the column’s $CO_2$ removal efficiency $\eta$.

$$\eta = 1 - e^{-\left( \frac{a_e}{A} \right)} \quad (25)$$

Where, the constant $A$ is the ratio $u_y/ZRTK_y$.

**MATERIALS AND METHODS**

**Experimental Procedure**

The setup is made up of an absorption column as the main unit. This column had an internal diameter of 0.23 $m$ and was packed with glass
spheres of diameter 16 mm to a height of 0.35 m with other supporting units being a 200L solvent tank, biogas and carbon dioxide canisters, gas and liquid flow meters and a gas analyzer. The flow chart is represented in Figure 2. A solution of volume 200 L and a concentration of 0.1 gmole/L solution of aqueous sodium hydroxide was prepared by dissolving NaOH flakes into distilled water at room temperature to make 200 L of the aqueous solution. This solution was pumped to the top of the column via a liquid rotameter and the flow regulated by a valve. To ensure that the column operates as a plug flow reactor, the solvent was evenly distributed over the column area S at the top of the column using a liquid nozzle. On the other hand, the gas stream with carbon dioxide mole fraction $y_a$, was delivered to the bottom of the column by connecting pipes through the gas rotameter. In this stream $y_a$, was set by regulating the flow of biogas and pure CO$_2$ to the mixing chamber and confirmed by the gas analyser. The two streams interacted counter currently in the column with the solvent leaving at the bottom while the biomethane, with CO$_2$ mole fraction $y_b$, exited at the top. The process was left to run for five minutes to attain steady state operation before $y_b$ was recorded at the sampling point 2. The operating range of the experimental factors are presented in Table 1.

**Figure 2:** The flow chart for biogas upgrading process used for evaluating the effective area and the column efficiency

![Flow Chart](image)

**Table 1: Range of experimental factors**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_y (m^3/m^2.s)$</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>$u_x (m^3/m^2.s)$</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>OH$^-$ (gmol/L)</td>
<td>0.1</td>
<td>1.0</td>
</tr>
<tr>
<td>$y_a (v/v)$</td>
<td>0.45</td>
<td>0.55</td>
</tr>
</tbody>
</table>

The influence of each of the variable were separately ascertained by varying its magnitude within the set range, keeping the other variables constant. The fractional effective area $a_e/a_e$, was then calculated and plotted against the variable.

**RESULTS AND DISCUSSIONS**

**Effect of Solvent Superficial Velocity**

The effect of the solvent superficial velocity $u_x$ on the fractional effective area was determined by increasing $u_x$ from 0.1 to 0.3 m/s. The calculated values of the fractional effective area $a_e/a_p$, were then plotted against $u_x$, at three
different gas superficial velocities $u_y$ as shown in Figure 3.

**Figure 3:** Variation of the fractional effective area $a_e/a_p$, with solvent superficial velocity $u_x$, at three gas velocities with constant solvent concentration and CO$_2$ mole fraction $\chi_a$ in the gas feed.

From the plots, $a_e/a_p$ increases with increase in $u_x$. When $u_y$ is maintained at 0.1 m/s, $a_e/a_p$ increased by 44.27% and was at 41.46% and 41.91% when $u_y$ was fixed at 0.2 and 0.3 m/s respectively. These findings suggest that the effective area $a_e$ is greatly influenced by the solvent superficial velocity $u_x$.

The column efficiency $\eta$, is a function of the effective area $a_e$. In evaluating variation of $\eta$ with $u_x$, the individual equations relating $a_e/a_p$ with $u_x$ is substituted to Eq. (25) and the results plotted in Figure 4.

From the plots in Figure 4, $\eta$ increases with $u_x$ approaching the 100% asymptote. The increase is attributed to increased rate of surface renewal in the interface between the phases by the solvent stream thus increasing the rate of forward reaction. Higher values of the gas superficial velocity $u_y$, reduces the gas’ residence time in the column and in the process increase the value of $y_b$.

**Figure 4:** The effect of solvent superficial velocity on the column efficiency

**Effect of Gas Superficial Velocity**

The effect of the gas superficial velocity $u_y$, on the fractional effective area and the column efficiency $\eta$, was also investigated. While keeping all the other factors constant, $u_y$ was increased from 0.1 to 0.3 m/s and the fractional effective
area \(\frac{a_e}{a_p}\) calculated over the range and plotted against \(u_y\) as in Figure 5.

The fractional effective area \(\frac{a_e}{a_p}\) decreases marginally with increase in \(u_y\). The percentage reduction was 0.45, 1.02 and 1.16% when \(u_x\) was fixed at 0.1, 0.2 and 0.3 m/s respectively. These figures are kept low by the high reaction rate between the solute and solvent molecules making the effect of the reduced residence time with \(u_y\) negligible. The effect of the increasing \(u_y\) on the \(CO_2\) removal efficiency is presented in Figure 6.

The column efficiency decreases with increase in \(u_y\). Increasing \(u_y\) reduces the liquid-to-gas (L/G) ratio in the column, which implies that for a given amount of \(OH^-\) molecules per unit time available for the reaction, there will be an oversupply of \(CO_2\) molecules that exits the bed unreacted increasing the value of \(y_b\) in the effluent gas. An increase in \(u_y\) reduces eddy diffusion of the solute molecules in the bulk of the gas phase making the effective area a weak function of gas superficial velocity.

**Figure 5:** The variation of fractional effective area with the gas superficial velocity \(u_y\).

![Figure 5](image1)

**Figure 6:** Variation of column efficiency with gas superficial velocity at three different solvent superficial velocities

![Figure 6](image2)

**Effect of Solvent Concentration**

To assess the effect of the solvent concentration of the effective area, the column was operated with the concentration increases 0.1 to 1.0 \(gmol/L\) while keeping the other variables constant. The effective area \(a_e\) was then calculated over this range and plotted in Figure 7.
Figure 7: A plot of the variation of fractional effective area with the solvent concentration at different solvent superficial velocities

The fractional effective area $a_e/a_p$, increase with increase in the concentration of the solvent. The percentage increase was at 192.9%, 134.8% and 109.5% when the solvent superficial velocity is set at 0.1, 0.2 and 0.3 m/s respectively. These findings shows that the effective area is a function of the solvent concentration, however, as the concentration increases $CO_2$ molecules start to accumulate in the reaction zone within the liquid film, slowing the reaction, and in the process slow the increase of the fractional effective area $a_e/a_p$. This explains the slope of the graphs in Figure 7.

The effect of the solvent concentration on $CO_2$ removal efficiency is evaluated using equation 25 and the results plotted in Figure 8.

Figure 8: Pot Variation of the column efficiency with solvent concentration.

From the plots, a high solvent concentration strongly influences $CO_2$ removal efficiency in the column.

Effect of $CO_2$ molar concentration
All the variables were kept constant as $CO_2$ mole fraction in the gas feed $y_a$, was increased from 0.45 to 0.55. The fractional effective area was calculated at three solvent superficial velocities and plotted against $y_a$ as presented in Figure 9.
Figure 9: Variation of the effective area with CO$_2$ mole fraction in the gas feed year

The fractional effective area increased marginally over the operating range of $y_a$. The increase was at 17.9, 16.5 and 29.6% when $u_x$ was fixed at 0.1, 0.2 and 0.3 m/s respectively.

Based on the two-film model, the driving force in the gas film is the concentration gradient between the bulk of the gas and the gas-liquid interface. An increase in $y_a$ in the gas bulk increases the concentration gradient in the gas film thus increasing the mass flux of the solute molecules across the film this has the effect of increasing the rate of absorption. However, with a constant solvent superficial velocity, there will be an accumulation of carbonate molecules in the reaction zone within the liquid film which reduces the effective area by blocking the diffusion of the solute molecules within the liquid film to the reaction zone. At low solvent concentration, this zone is located way into the liquid film and the solute molecules have to diffuse through a liquid film of thickness $\delta x$. A plot of CO$_2$ removal efficiency was plotted against $y_a$ in Figure 10.

Figure 10: The effect carbon dioxide mole fraction on the column efficiency.

Increasing CO$_2$ mole fraction creates molecular instability, referred as the Marangoni effects, arising from a variety of physico-chemical interactions which generates interfacial convective flows and creates forces associated with surface tension gradients. The flows thus created contributes to renewal of solute the molecules at the interface sharply increasing the effective area for mass transfer $a_e$ and aid the chemisorption process. the column efficiency thus increases with increase in CO$_2$ mole fraction in the gas feed to the column.

CONCLUSIONS AND RECOMMENDATIONS

The influence of the column parameters on the effective mass transfer coefficient and CO$_2$ removal efficiency was investigated in an absorption column of internal diameter 0.23 m and packed to a height of 0.35 m with glass
spheres with a diameter of 0.016m and operated at room temperature and pressure.

The experimental results showed that the effective area is directly proportional to the magnitude of the solvent superficial velocity \( u_x \), the solvent concentration \([OH^-]\) and \( CO_2 \) mole fraction in the gas fed to the column, while being inversely proportional to the gas superficial velocity \( u_y \). It is greatly influenced by the solvent to gas superficial velocities \( u_x/u_y \) and the solvent-solute concentrations \([OH^-]/y_a \) and to optimize the process of chemisorption, these ratios must be minimized.

REFERENCES


**APPENDIX**

**Appendix 1: Nomenclature**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_y'$</td>
<td>Apparent gas phase mass transfer coefficient</td>
<td>moles/m$^3$.hr.atm</td>
</tr>
<tr>
<td>$[OH^-]$</td>
<td>Concentration of the solvent</td>
<td>moles/m$^3$</td>
</tr>
<tr>
<td>$\alpha_e/\alpha_p$</td>
<td>Fractional effective area for mass transfer</td>
<td>-</td>
</tr>
<tr>
<td>$CO_2$</td>
<td>Carbon dioxide</td>
<td>-</td>
</tr>
<tr>
<td>$D_{CO_2,x}$</td>
<td>Diffusion coefficient of CO$_2$ in the liquid film.</td>
<td>m$^2$/s</td>
</tr>
<tr>
<td>$k_y$</td>
<td>Overall mass transfer coefficient based on the gas film coefficient</td>
<td>kg.moles/m$^3$.hr.atm</td>
</tr>
<tr>
<td>$Ha$</td>
<td>Hatta Number</td>
<td>-</td>
</tr>
<tr>
<td>$\gamma_a$</td>
<td>Carbon dioxide mole fraction in the inlet gas.</td>
<td>-</td>
</tr>
<tr>
<td>$\alpha_e$</td>
<td>Effective mass transfer area</td>
<td>m$^2$/m$^3$</td>
</tr>
<tr>
<td>$\alpha_p$</td>
<td>Surface area for the packing</td>
<td>m$^2$/m$^3$</td>
</tr>
<tr>
<td>$\alpha_w$</td>
<td>Wetted surface area for the packing</td>
<td>m$^2$/m$^3$</td>
</tr>
<tr>
<td>$k_1$</td>
<td>First order reaction rate constant.</td>
<td>m/hr</td>
</tr>
<tr>
<td>$k_x$</td>
<td>Liquid film mass transfer coefficient</td>
<td>m/s</td>
</tr>
<tr>
<td>$k_y$</td>
<td>Gas film mass transfer coefficient.</td>
<td>m/s</td>
</tr>
<tr>
<td>$u_x$</td>
<td>Solvent superficial velocity</td>
<td>m$^3$/m$^2$s</td>
</tr>
<tr>
<td>$u_y$</td>
<td>Gas superficial velocity</td>
<td>m$^3$/m$^2$s</td>
</tr>
<tr>
<td>$\gamma_b$</td>
<td>CO$_2$ mole fraction for the gas exiting the column</td>
<td>-</td>
</tr>
<tr>
<td>$Z$</td>
<td>Height of the column.</td>
<td>m</td>
</tr>
<tr>
<td>$\beta^{\infty}$</td>
<td>Infinite enhancement factor</td>
<td>-</td>
</tr>
<tr>
<td>$k_H$</td>
<td>Henry’s constant for the system</td>
<td>mole/m$^3$.Pa</td>
</tr>
<tr>
<td>$P$</td>
<td>Operating Pressure</td>
<td>atm</td>
</tr>
<tr>
<td>$R$</td>
<td>Universal gas constant</td>
<td>J/mol. K</td>
</tr>
<tr>
<td>$S$</td>
<td>Column’s base area</td>
<td>m$^2$</td>
</tr>
<tr>
<td>$T$</td>
<td>Standard temperature</td>
<td>K</td>
</tr>
<tr>
<td>$V$</td>
<td>Gas molar flow rate</td>
<td>moles/s</td>
</tr>
<tr>
<td>$y^*$</td>
<td>Concentration of the solute in equilibrium with the liquid</td>
<td>-</td>
</tr>
</tbody>
</table>

**Subscripts**

<table>
<thead>
<tr>
<th>Subscript</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x$</td>
<td>Liquid phase</td>
</tr>
<tr>
<td>$y$</td>
<td>Gas phase</td>
</tr>
<tr>
<td>$p$</td>
<td>Geometric surface</td>
</tr>
<tr>
<td>$w$</td>
<td>Wetted surface</td>
</tr>
<tr>
<td>$e$</td>
<td>Effective surface</td>
</tr>
</tbody>
</table>

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