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Liquid Phase Mass Transfer Coefficient of Carbon Dioxide Absorption by Water Droplet

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Abstract

A new experimental set-up was established to measure liquid phase mass transfer coefficient of CO_2 absorption by single water droplet. The experiments were performed at 303.65 K and 323.15 K, with a droplet falling height of 0.41 m and 0.59 m. The droplet formation time varies from 0.352 s to 2.315 s. The droplet diameter changes little and is around 2.5 mm. The effects of temperature, droplet falling height and droplet formation time on CO_2 absorption by individual water droplet are discussed.

Keywords: Mass transfer coefficient; CO_2; Water droplet; Absorption

1. Introduction

Spray column is one of the important types of columns that is used for bulk removal of CO_2 from a gaseous stream in industry. It provides a very large contact surface area between gas-liquid phases. A depth understanding of the mass transfer characteristics in the spray column is important for optimization design of the column and the selection of absorbent. In the spray column, liquid disperses in the gas in the form of liquid droplets. Mass transfer between CO_2 and water droplets is investigated in this work.

Whitman et al. [1] and Dixon and Russell [2] studied CO_2 absorption by single water droplet. The effect of droplet formation time on overall mass transfer coefficient was discussed. A comparison of their

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measured mass transfer coefficient is shown in Table 1. The difference is because Whitman et al. obtained the mass transfer during drop formation by the extrapolation method while Dixon and Russell directly measured the mass transfer during formation by experiments. Srinivasan and Aiken [3] studied CO_2 absorption by a cylindrical jet of several water droplets with an average droplet size 82.4 μm. The following correlation was obtained:

$$Sh = 0.14(Sc)^{1/2}(We)^{1/2}(Re)^{5/16} \tag{1}$$

Table 1. A Comparison of Measured Mass Transfer Coefficients of CO_2 Absorbed by Water Droplets in the Literature

	t_1 [s]	Re_d	k_L [cm/s] during formation	k_L [cm/s] during fall
Whitman et al. [1] (1926)	0.5		0.0012	0.0747
	4.94		0.0011	0.0939
Dixon and Russell [2] (1950)	0.5		0.0314	0.0294
	5		0.0057	0.0089
Srinivasan and Aiken [3] (1988)		377-789	-	0.24-0.64

In this work, a new experimental apparatus was established to study CO_2 absorption by the unit part of a spray which is an individual droplet. The effects of temperature, droplet falling height and droplet formation time on liquid phase mass transfer coefficient of CO_2 absorption by single water droplet are studied.

2. Experimental Setup

This system produces individual droplet by pushing the liquid through a needle with the help of pressurized nitrogen. The outer diameter of the needle is 0.5144 mm and the inner diameter is 0.26 mm. The droplets fall through a gas chamber one by one and finally deposit under kerosene. Pure CO_2 is filled in the gas chamber to eliminate the gas side mass transfer resistance. A temperature control box was built outside the chamber in order to perform the absorption experiments at different temperatures. The pressure inside the chamber keeps constant and the same as the atmosphere by an overflow section. The volume flow rate of CO_2 was measured by a soap film flow meter to calculate the absorption rate. A high speed camera system was used to determine the size of droplets and the droplet formation time. The sketch of the experimental setup is shown in Figure 1. The absorption of CO_2 into the kerosene can be measured before the droplets start dripping. The results from this blank experiment will be subtracted to get how much of CO_2 is absorbed by water droplets. Because the density of kerosene is much lower than water, the droplets deposit under kerosene very fast. Hence, the coalescence effect can be eliminated.

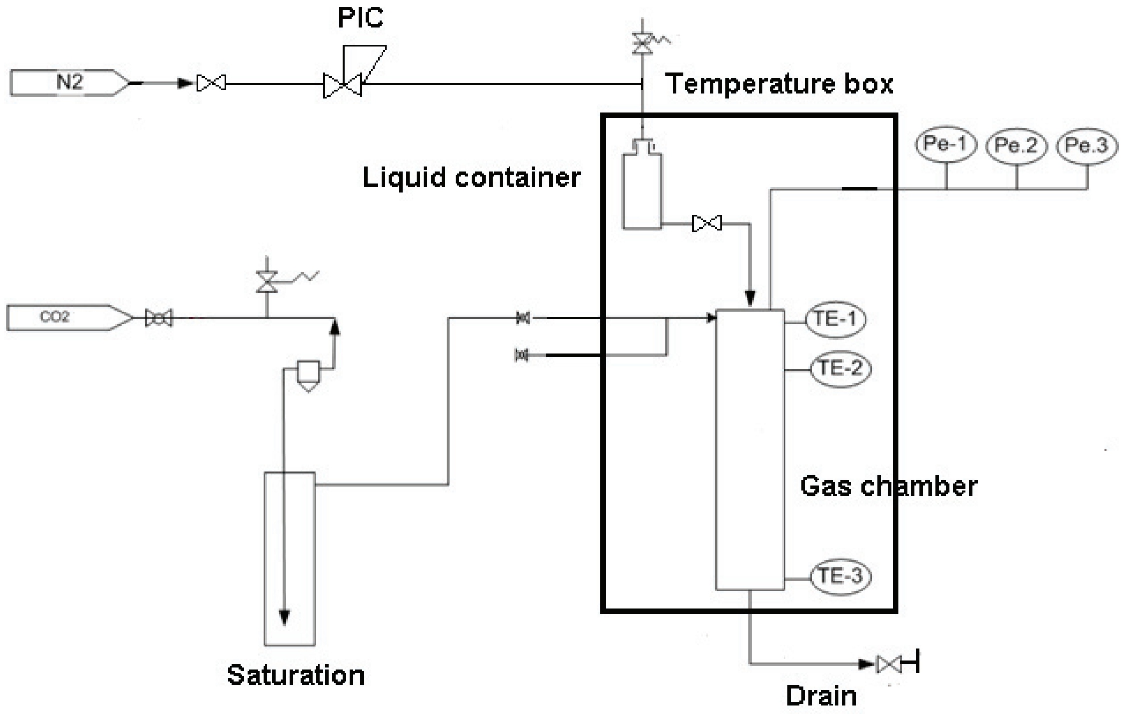

Figure 1: The sketch of a novel experimental setup for studying the absorption of CO_2 by water droplets.

3. Mass Transfer Coefficient Calculation

Due to the fact that the molecular diffusion coefficients of solutes are several orders of magnitude greater in gases than in liquids, the gas phase mass transfer coefficient is much greater than liquid phase mass transfer coefficient in most instances which causes that the absorption process is controlled by the liquid phase resistance [3]. The liquid phase mass transfer coefficient between liquid droplets and gas without chemical reaction was derived based on the following assumptions:

(1) The droplet keeps spherical during formation and fall.
(2) The droplet grows at a uniform volumetric rate during formation.
(3) The droplet diameter and droplet formation time keep constant during each measurement.
(4) The absorption is in equilibrium at the gas-liquid interface and in accordance with Henry's law.

The mass balance equation of gas absorption into liquid droplets without chemical reaction is given by:

$$V_d(dC/dt) = k_L A_d (C_e - C) \tag{2}$$

Integrating eq 2 with boundary conditions (at t = 0, C = 0; at t = t, C = C) gives:

$$C_e - C = C_e e^{-6k_L t/d} \tag{3}$$

The mass transfer amount of gas absorption into a liquid droplet during its lifetime τ is:

$$M = \int_0^\tau k_L A_d (C_e - C) dt = \int_0^\tau k_L A_d C_e e^{-6k_L t/d} dt = A_d C_e d(1 - e^{-6k_L \tau/d})/6 \tag{4}$$

The mass transfer amount of gas absorption into a liquid droplet during infinite time is:

$$M_\infty = \int_0^\infty k_L A_d (C_e - C) dt = \int_0^\infty k_L A_d C_e e^{-6k_L t/d} dt = A_d C_e d/6 \tag{5}$$

The fractional approach to equilibrium is defined by:

$$F = M/M_\infty = 1 - e^{-6k_L \tau/d} \tag{6}$$

Rearranging yields:

$$k_L = (d/6\tau)\ln(1/(1-F)) \tag{7}$$

It is necessary to calculate F when M and M_∞ must first be calculated:

$$M = (-\mathrm{d}n/\mathrm{d}t)/\varphi \tag{8}$$

Here $-\mathrm{d}n/\mathrm{d}t$ means the mole numbers of CO_2 that being absorbed per second. φ means the numbers of droplets per second. Therefore $(-\mathrm{d}n/\mathrm{d}t)/\varphi$ is the mole numbers of CO_2 that being absorbed by one droplet during its lifetime.

$$M_\infty = V_2 C_e = V_2 P/H \tag{9}$$

Hence:

$$F = M/M_\infty = (-\mathrm{d}n/\mathrm{d}t)H/(V_2 P\varphi) \tag{10}$$

Therefore, liquid phase mass transfer coefficient of gas absorption into liquid droplets without chemical reaction can be calculated from eqs 7 and 10.

4. Results and Discussion

The average liquid phase mass transfer coefficients of CO_2 absorption into water droplets during formation and fall at different temperatures, droplet formation times and droplet falling heights are found by experiments. The measured liquid phase mass transfer coefficients are given in Table 2. The variations of liquid phase mass transfer coefficients of CO_2 absorption into water droplets during formation and a falling height of 0.59 m as a function of droplet formation time at 303.65 K and 323.15 K were shown in Figure 2. The liquid phase mass transfer coefficient of CO_2 absorption into water droplets increases as the temperature rises and decreases as the droplet formation time increases. When the droplet formation time increases, the convection inside the water droplet decays, therefore the mass transfer coefficient decreases. Because CO_2 is slightly soluble in water, the solubility affects little on the mass transfer. When the temperature increases, the diffusivity of CO_2 in water increases, therefore the liquid phase mass transfer coefficient increases. The changes of liquid phase mass transfer coefficients of CO_2 absorption into water droplets during formation and a fall of 0.41 m and 0.59 m respectively as a function of droplet formation time at 323.15 K were displayed in Figure 3. The average liquid phase mass transfer coefficient increases as the droplet falling height increases. This is because the instantaneous mass transfer coefficient increases as the droplet velocity increases during the droplet free fall.

Table 2. The Measured Liquid Phase Mass Transfer Coefficients of CO_2 Absorption by Water Droplets during Formation and Fall[a]

T [K]	P [Pa]	h [m]	-dn/dt [mol/s]	φ [s-1]	t_1 [s]	t_2 [s]	d_2 [m]	H [Pa·m^3/mol]	k_L [cm/s]
303.65	100000	0.59	2.631E-07	2.837	0.352	0.3557	0.002533	3526	0.0253
303.65	100060	0.59	1.538E-07	1.747	0.572	0.3559	0.002404	3526	0.0203
303.65	99810	0.59	0.497E-07	0.759	1.318	0.3560	0.002543	3526	0.0064
303.65	99980	0.59	0.404E-07	0.487	2.053	0.3552	0.002586	3526	0.0055
303.65	100550	0.41	1.704E-07	2.424	0.413	0.2941	0.002540	3526	0.0173
303.65	100610	0.41	0.925E-07	1.556	0.643	0.2955	0.002434	3526	0.0116
323.15	100710	0.59	2.378E-07	2.878	0.347	0.3552	0.002448	5219	0.0405
323.15	102420	0.59	1.626E-07	1.732	0.577	0.3556	0.002458	5219	0.0355
323.15	102380	0.59	0.678E-07	0.718	1.393	0.3561	0.002453	5219	0.0183
323.15	100740	0.59	0.606E-07	0.468	2.137	0.3550	0.002603	5219	0.0177
323.15	99760	0.41	1.866E-07	2.532	0.395	0.2950	0.002523	5219	0.0321
323.15	99810	0.41	1.217E-07	1.660	0.602	0.2983	0.002432	5219	0.0267
323.15	100680	0.41	0.553E-07	0.656	1.524	0.2951	0.002563	5219	0.0127
323.15	100430	0.41	0.464E-07	0.432	2.315	0.2957	0.002570	5219	0.0126

[a]: Henry's coefficients of CO_2 in water refer to the data from Versteeg and van Swaaij [4].

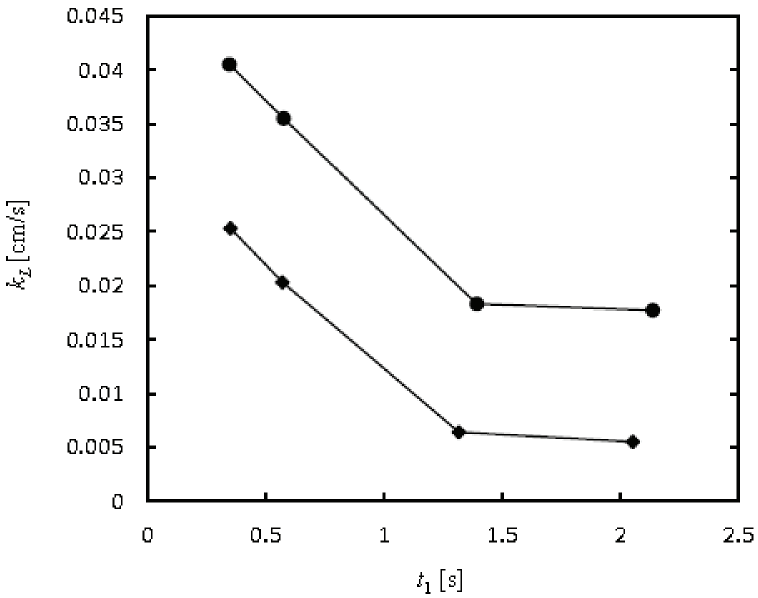

Figure 2. The variation of liquid phase mass transfer coefficient k_L of CO_2 into water droplets during formation and a fall of 0.59 m as a function of droplet formation time t_1 at different temperatures. ♦, 303.65 K; ●, 323.15 K.

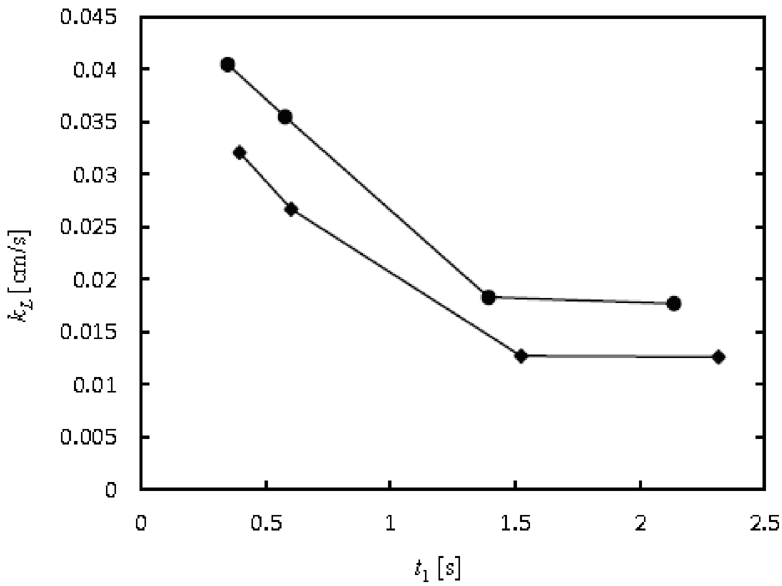

Figure 3. The change of liquid phase mass transfer coefficient k_L of CO_2 into water droplets during formation and fall as a function of droplet formation time t_1 at 323.15 K. ♦, droplets fall through a height of 0.41 m; ●, droplets fall through a height of 0.59 m.

5. Conclusions

A new experimental apparatus was built to study mass transfer between CO_2 and single water droplets. The liquid phase mass transfer coefficient of CO_2 absorption by water droplets was measured at different temperatures, droplet formation times and droplet falling heights. The mass transfer coefficient increases as temperature and droplet falling height increases. The mass transfer coefficient decreases as droplet formation time increases.

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Nomenclature

A	droplet surface area, m^2
C	concentration of gas in the liquid droplet, mol/m^3
d	droplet diameter, m
D	diffusion coefficient, m^2/s
F	fractional approach to equilibrium
h	henry's coefficient, $Pa{\cdot}m^3/mol$
H	Henry's coefficient, $Pa{\cdot}m^3/mol$
k_L	liquid phase mass transfer coefficient, m/s or cm/s
M	mass transfer amount of gas absorption into a liquid droplet, mol
n	mole numbers of gas in the gas chamber, mol
$-\mathrm{d}n/\mathrm{d}t$	absorption rate of gas in the liquid droplet, mol/s
P	pressure in the gas chamber, Pa
Re	Reynolds number, $\rho ud/\mu$
Sc	Schmidt number, $\mu/(\rho D)$
Sh	Sherwood number, $k_L d/D$
t	absorption time, s
t_1	drop formation time, s
t_2	droplet falling time, s
T	droplet falling height, m
u	droplet velocity, m/s
V	droplet volume, m^3

We	Weber number, $u^2\rho d/\sigma$
ρ	density, kg/m^3
μ	dynamic viscosity, kg/(m·s)
σ	surface tension, N/m
τ	droplet lifetime during formation and fall, s
φ	droplet formation rate, s^{-1}
Subscripts	
d	droplet
e	equilibrium
L	liquid phase
∞	infinite time
1	condition for the droplet formation
2	condition for the droplet fall

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