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A Notes on Mass Transfer of Dispersed Phase in Isothermal Two-Phase Bubble Column Reactor

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Abstract: A precise knowledge of two-Phase interfacial mass transfer mechanism is very important for designing and scaling up a bubble column reactor. In this study, equations have been derived to describe the motion of the phases and the mechanism of integral inter-phase mass transfer during the dissolution of dispersed phase in continuous phase. Different conditions for complete dissolution or absorption of dispersed phase in continuous phase at different operational mode has also been discussed.

Key words: Bubble column, holdup, inter-phase mass transfer, absorption coefficient

INTRODUCTION

Two-Phase mass transfer is an important process in a number of chemical engineering unit operations such as gas-liquid and gas-liquid-solid reaction, distillation and absorption. It is a common problem to predict the mass transfer rate in a variety of chemical synthesis, petrochemical manufacturing, energy transformation, environmental engineering and biochemical engineering. Thus, it is necessary to have a better understanding of the mechanism and characteristics of gas-liquid mass transfer phenomena. Researches on the relationship, interactions and influences of chemical reaction and mass transfer are also significant for developing efficient gas-liquid mass transfer and for the optimal design of novel commercial gas-liquid Two-Phase reactors. Kang *et al.*[1]; Sada *et al.*[2]; Shimizu *et al.*[3]; Galin and Churmaev[4] discussed the mass transfer phenomena in different types of bubble column and developed different correlations with phase holdup, concentration of components and with other physical and geometrical variables. But very few literatures are available regarding the mechanism of mass transfer between the phases in Two-Phase bubble column reactor. In this study the mechanism of mass transfer between the phases during the dissolution of dispersed phase in continuous phase has been discussed.

Dissolution of a dispersed gas phase in a liquid: Let us consider the dissolution or absorption of a dispersed gas phase in a continuous liquid phase, under co and countercurrent flow conditions in a vertical bubble column reactor. Assuming the concentrations of a component in the dispersed and continuous phases are x_d and x_c respectively. The two mass conservation equations for dispersed and continuous phases in Eq. 1, 2 and material balance in Eq.3 in the continuous liquid phase can be written in the form of dimensionless quantity limiting the investigation to steady state absorption as

$$\rho_d \frac{d}{dz}[(\gamma-\lambda)\varepsilon]+k(x^*-x_c)=0 \quad (1)$$

$$\rho_c \frac{d}{dz}[\lambda(1-\varepsilon)]+k(x^*-x_c)=0 \quad (2)$$

$$\frac{d}{dz}[\lambda x_c(1-\varepsilon)]+k(x^*-x_c)=0 \quad (3)$$

where $\gamma = (u_c-u_d)/u_o$, $\lambda = u_c/u_o$, $k = KL/\epsilon_o u_o$, $z = Z/L$. u_o and ϵ_o are the relative velocity and gas holdup at their point of introduction into the column. It is assumed that the volumes of the materials have practically no effect on the specific volumes of the phases or mass-transfer coefficient K, so these quantities are constant over the height of the column. Uniform flows in the column were considered with the Z axis oriented along the direction of motion of the dispersed phase. Values of λ less than zero correspond to upward co-current flow with the gas moving faster than liquid, values $0 \le \lambda$ 1 correspond to countercurrent flow and values $\lambda>1$ to downward co-current flow with the gas lagging behind the liquid.

The two first integrals explain in Eq.1 and 2 can be represented as follows,

$$\rho_d(\gamma-\lambda)\varepsilon-\rho_c(1-\varepsilon)\lambda = b_1 \quad (4)$$

$$(\rho_c - x_c)(1-\varepsilon)\lambda = b_2 \quad (5)$$

where, b_1 and b_2 are constants. Obviously, $x_c << \rho_c$, so that it follows from the Eq. 5

$$\lambda = \lambda_0(1-\varepsilon)^{-1}, \quad \lambda_0 = u_{c0}/u_0$$

Here u_{c0} is the velocity of continuous phase in the absence of disperse phase. In order to point out the possible regimes of dissolution, only the expression describing the absorption of gas far from saturation conditions is considered (such dissolution is realized when the dissolved gas takes part in a reaction). Assuming $x_c \ll x^*$, from Eq. 1 one get the equation as;

$$\rho_d \frac{d}{dz}[(\gamma - \lambda)\varepsilon] + kx^* = 0 \quad (6)$$

Solution of the above equation gives the values of u and K appearing in the definition of γ, λ and k. Specifically, the relationship obtained by Levich[5] has been used here for small and moderate Reynolds numbers Re up to approximately equal to 700. The solution for u and K can be expressed as;

$$u_c - u_d = C_1 \frac{\rho_c r^2}{\mu} f_1(\varepsilon) \quad (7)$$

$$K = C_2 \left(\frac{E\rho_c \varepsilon g f_1(\varepsilon)}{\mu} \right)^{0.5} f_2(\varepsilon) r^{2.5} \quad (8)$$

where $f_1(\varepsilon)$ and $f_2(\varepsilon)$ are correction functions which take into account the hindered nature of the bubble flow and the effects of diffusion from their surfaces. At small Reynolds number, $C_1 = 2/9$, $C_2 = 8/3(\pi/3)^{0.5}$ and at large Reynolds number, $C_1 = 1/9$, $C_2 = 8/3(\pi/2)^{0.5}$. Calculation of Treyabal[6] and Brounshtein[7] also leads to Eq. 7 and 8 with rather different values of C_1 and C_2. For the negligible break-up and coalescence of bubbles in the process, it is possible to write the following Equation:

$$C_3 = \varepsilon/\sigma = \text{const}, \quad r = r_0(\varepsilon/\varepsilon_0)^{0.33} \quad (9)$$

Therefore from Eq. 1-9 the following relationships can be found in the study $f_1 = f_2 = 1$;

$$\gamma = \left(\frac{\varepsilon}{\varepsilon_0}\right)^{2/3}, \quad k = 2\psi\left(\frac{\varepsilon}{\varepsilon_0}\right)^{5/6} \frac{\varepsilon_0 \rho_d}{x^*} \quad (10)$$

$$\psi = \frac{C_2 x^*}{2\varepsilon_0 \rho_d} \left(\frac{E\rho_c \varepsilon g}{\mu}\right)^{0.5} \frac{C_3 L r_0^{2.5}}{\varepsilon_0 u_0} \quad (11)$$

Introducing the unknown $\varepsilon_R = \varepsilon/\varepsilon_0$ and making use of Eq. 10 and 11, the following boundary value problem is found from Eq. 6:

$$\frac{d}{dz}[\varepsilon_R(\varepsilon_R^{2/3} - \lambda)] + 2\psi\varepsilon_R^{5/6} = 0, \quad \varepsilon_R(0) = 1 \quad (12)$$

The solution of this problem can be written as:

$$z = \frac{1}{\psi}[(1 - \varepsilon_R^{5/6}) - 3\lambda(1 - \varepsilon_R^{1/6})] \quad (13)$$

Condition for dissolution in upward co-current bubbly flow (λ<0): The quantity ε_R in Eq. 13 decreases monotonically from unity when z = 0 to zero when $z = z_0$, where:

$$z_0 = \frac{1}{\psi}[1 - 3\lambda] \rangle 0 \quad (14)$$

The quantity z_0 determines the height at which the bubbles completely disappear, rapidly decreases as the parameter ι increases and the quantity λ decreases. One can calculate the value of ι from Eq. 14 with the known values of Z_0 and λ from experiment. Then the validation of the model equation for mass transfer coefficient by Eq. 10 and 11 can be proved with the experimental values of mass transfer coefficient[8].

Condition for dissolution in downward co-current bubbly flow (λ>1): The relationship expressing absorption in this type of flow (λ>1) is obtained from Eq. 12 and 13 after changing the sign of z. In this study, in Eq. 14 the value of z_0 is replaced by the following relationship:

$$z_0 = \frac{1}{\psi}[3\lambda - 1] \quad (15)$$

It can be seen that for a given value of λ, the absorption or dissolution is accomplished more rapidly in upward co-current flow, where the dispersed phase moves faster than the liquid. For the validity of this condition can be pursued with the published experimental work[9,10].

Condition for dissolution in countercurrent bubbly flow ($0 \le \lambda \le 1$): If t he gas phase dissolves, the dimensions of the gas bubbles and their relative velocity (u_c-u_d)

decreases until at some level z_i and their velocity is no longer equal to the velocity of the countercurrent liquid flow that is, until 'flooding' begins. This level z_i can be determined from Eq. 12 and 13 with the condition $\varepsilon_R(z) = \varepsilon_R(z_i) = \varepsilon_{Ri} = \lambda^{1.5}$ and can be obtained as:

$$z_i = \frac{1}{\psi}(1 - 3\lambda + 2\lambda^{5/4}) \tag{16}$$

If $z_i > 1$, no flooding will be there in the countercurrent column. In this case, the absorption coefficient at z = 1 can be expressed as:

$$A = 1 - \varepsilon_R(1)\frac{\varepsilon_R^{2/3}(1) - \lambda}{1 - \lambda} \tag{17}$$

If $z_i < 1$, flooding will occur at some position in the working section of the column due to the reverse flow of the fine bubbles starting at the level $z = z_i$. To do this a coordinate $z = z_i - z$ has to be introduced and to make use of the results obtained above for the case of downward co-current flow. By introducing the new unknown $\varepsilon_{ri} = \varepsilon/\varepsilon_i$, where ε_i volume concentration of the rising bubbles at $z = z_i$ and new parameters Ψ_i, λ_i, expressed in terms of ϵ_i, r_i in the same way that Ψ in Eq. 10 and 11 and simplified form for ε_{ri} can be obtained as:

$$(1 - \varepsilon_{ri}^{5/6}) - 3\lambda_i(1 - \varepsilon_{ri}^{1/6}) = \varepsilon_{ri}^{1/6}(3 - \varepsilon_{ri}^{2/3}) - 2 = -\psi_i y \tag{18}$$

Complete dissolution of the gas bubbles will occur in the column if

$$y = \frac{1}{\psi_i}(3\lambda_i - 1) = \frac{2}{\psi_i} \le z_i \tag{19}$$

Complete dissolution of the entire amount of the gas introduced into the column is achieved when condition of Eq. 19 is satisfied. If the objective is to absorb a maximum amount of gas in the liquid in a countercurrent column, it is desirable to select different parameters like L, ε etc. in such a way that the following relationships are satisfied:

$$z_i = 1 - \varepsilon_n, \quad \varepsilon_{ri} \le 1; \quad y \le z_i \tag{20}$$

It should be noted that the presence of flooding in the column and the subsequent entrainment of the fine gas bubbles by the liquid flow lead to some equalization of the gas content over the height of the column. The total volumetric concentrations in sections of the column where there are both upward and downwardmotion of bubbles are given by the relationship

$$\varepsilon(z) = \varepsilon_0\varepsilon_R(z) + \varepsilon_i\varepsilon_n(z_i - z) \tag{21}$$

for $0 \le z \le z_i$ and $0 \le z_i - z \le y$. It is easy to observe that these conclusions will not change qualitatively, if the simplifying assumptions $\varepsilon << 1$, $x << x^*$, etc., are infringed. However close to saturation ($x \sim x^*$) it is possible for a new steady state absorption regime to appear which differs somewhat qualitatively from the conditions considered above. This can also be proved by the experimental data obtained by Voigt and Schügerl[11]; Voigt *et al.*[12]; Chen *et al.*[13]. The model parameter in each condition discussed above will be different for different operational flow mode.

CONCLUSION

The following conclusion may be drawn from this study:

- Analysis of dissolutions of dispersed phases in continuous liquid phases in Two-Phase bubble column reactor has been done from the derived Equation.
- The quantity z_0 determines the height at which the bubbles completely disappear depending on the parameter λ and Ψ at different operational mode (co-current upward, countercurrent and co-current downward bubbly flow)
- For a given value of λ, the absorption or dissolution is accomplished more rapidly in upward co-current flow, where the dispersed phase moves faster than the continuous phase.
- Complete dissolution of the entire amount of the gas introduced into the column is achieved when condition in Eq. 18 is satisfied for countercurrent bubbly flow.
- The mechanism of dissolution of dispersed phase based on the model discussed can be utilized for the prediction of mass transfer coefficient with different operational flow conditions.

Nomenclature

b_1, b_2	Constants, [-]
C_1, C_2	Constants, [-]
E	Characterization factor, [-]
f_1, f_2	Correlation functions
K	Mass transfer coefficient, m s^{-1}
L	Length of the column, m
r	Radius of bubble or droplet, m

u Superficial velocity, m s^{-1}
x Concentrations, kg m^{-3}
x* Equilibrium concentration, kg m^{-3}
y Parameter in Eq. 18
Z Axis along the direction of motion of the dispersed phase, m
ε Fractional holdup of dispersed phase, [-]
ρ Density, kg m^{-3}
0 Relative
c Continuous
d Dispersed

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