

## **Flat-Film Model Of A Foam-Bed Contactor**

S. K. Jana, I. Arya, M. Lungu

Department of Chemical Engineering, Malaviya National Institute of Technology, Jaipur-  
302017, Rajasthan, India

### **Abstract**

*A flat film model of a gas-liquid foam-bed reactor has been developed for gas absorption accompanied by a fast chemical reaction. Experimental data and parameter values reported in the literature for the absorption of lean carbon-dioxide gas in sodium hydroxide solution in a foam-bed reactor in presence of a surfactant have been used to validate the model. Total area of the bubbles and their number at any time in the column, required for simulation of the model developed in the present work, were obtained from the correlations reported in the literature. Experiments were also performed to determine the bubble size in a foam column and compared with the values predicted from a model reported by the present author. The model predictions for the change of bubble volume agree well with the experimental data collected in the present work and also observed to compare well with the experimental data reported in the literature.*

**Keywords:** Flat film model, Foam-bed reactor, Gas absorption, Bubble volume measurement

### **1. Introduction**

A shallow pool of liquid containing a surfactant with a tall column of foam above it is termed a foam-bed reactor. During the last three decades numerous models have been reported in the literature (Biswas and Kumar [18]; Bhaskarwar and Kumar [22]; Sharma et al. [20], to name a few) for gas-liquid and gas-liquid-solid foam-bed reactors. It is reported [21] that a foam-bed reactor offers long gas-liquid contact time, low to moderate gas pressure drop, large gas-liquid interfacial area and high rate of mass transfer compared to conventional contactors. In a recent investigation, carbonation of hydrated

lime into PCC has been found to be substantially higher [17] in a slurry-foam reactor, in presence of Triton X-100 as the foaming agent, over that in a bubble column reactor.

The objective of the present work is to develop a new model of a foam-bed contactor considering mass transfer to occur into a flat film of area equivalent to the total area of all the bubbles in the foam column and to validate the model taking experimental data from literature. It is also intended to validate a model reported by the present author, for the change of bubble volume with time in a bubble column reactor using experimental data from literature.

## 2. Theory

Gas as a dispersed phase plays an important role in a variety of industrial contactors. Properties of gas bubbles, e.g., shape and size, relative motion between two phases, interface characteristics etc are significant parameters in physical and chemical operations as well as in mechanically agitated vessels. These include gas absorption, hydrogenation, fermentation, aeration, ore flotation, air lift pumps, air agitators, etc, to name a few. The objective in the cases of process operations is to produce smaller size of bubbles for large specific interfacial area and high rate of mass transfer in order to reduce the equipment size for a given production rate. This is especially important for such operations as fermentation and other biochemical reactions which proceed at a reasonably low rate. Although the bubble size at the time of detachment is obtained from a force balance, additional factors which are likely to affect the average bubble size  $d_b$  rising through a column of liquid are, the column diameter  $d_c$ , superficial velocity of gas  $U_G$ , and viscosity of the liquid,  $\mu_l$ . While the correlation proposed by Wilkinson et al. [15] shows (Table I) a decrease in the bubble size, most other correlations indicate an increase in the bubble size with an increase in the superficial velocity of gas.

If no other force except buoyancy is the cause of bubble detachment, a force balance yields [6],

$$\frac{4}{3} \pi R_b^3 (\rho_l - \rho_g) g = 2 \pi r_0 \gamma \cdot \cos \theta \cdot f\left(\frac{r_0}{C_c}\right) \quad (1)$$

Where,  $\theta$  is the angle of contact at the triple interface,  $C_c$  being the square root of the capillary constant,  $(2\gamma/\rho g)^{0.5}$ , and,  $f(r_0/C_c)$  is the shape factor which has a value equal to a 1 for a sphere.

, where  $k_l$  and  $k_g$  are the liquid and gas-phase mass-transfer coefficients, and  $k_s$  is the surface coefficient arising due to the presence of a thin layer of the surfactant at the gas-liquid.  $H'$  is the Henry's law constant defined by the equation

shape factor which has a value equal to 1 for a sphere. At the moment of detachment, if the bubble is assumed to spherical, issuing from a circular orifice having vertical axis, perfect wetting of the orifice by the liquid ( $\theta = 0$ ) and  $\rho_l \gg \rho_g$  and that for a spherical bubble, equation (1) may be rearranged to yield,

$$R_b = \left(\frac{3}{2} \frac{r_0 \gamma}{\rho_l \cdot g}\right)^{1/3} \quad (2)$$

Application of equation (2) for the ratio of bubble volume to orifice diameter yields

$$\frac{V_b}{d_0} = \frac{\pi \gamma}{\rho_l g} \quad (3)$$

For a liquid with a given density and a particular orifice diameter, therefore, bubble volume is directly proportional to surface tension.

### 2.1. Flat-film model for a foam-bed reactor

For absorption of a gas in liquid containing a surface-active agent, the overall mass-transfer coefficient can be estimated using the expression

$$\frac{1}{K_{l,OV}} = \frac{1}{k_l} + \frac{1}{k_s} + \frac{1}{H' k_G} \quad (4)$$

$$P_{A_i} = H' C_{A_i} \quad (5)$$

An instantaneous value of the liquid-phase mass-transfer coefficient can be estimated

$$\text{using the expression, } k_l = \sqrt{\frac{D_{AB}}{\pi \cdot t}} \quad (6)$$

For absorption of pure gas, gas-phase resistance can be considered negligible compared to the other terms and equation (4) can be written as

$$K_{l,OV} = \frac{k_s k_l}{k_l + k_s} \quad (7)$$

Moles of carbon-dioxide gas reacted in the reactor per unit time is obtained from (for a fast reaction)

$$N_A = K_{l,OV} \cdot A_T \cdot (C_{Ai} - 0) \quad (8)$$

For mass transfer with chemical reaction, the rate of gas absorption is enhanced and the mass-transfer coefficient with chemical reaction,  $k_{lr}$ , can be written as

$$k_{lr} = E_i k_l \quad (9)$$

, where  $E_i$  is the enhancement factor for gas absorption with chemical reaction.

Replacing  $k_l$  by  $k_{lr}$  in equation (7), substituting the expression for  $k_{lr}$  from equation (9) and rearranging it, one obtains

$$K_{l,ov} = \frac{E_i k_l k_s}{E_i k_l + k_s} \quad (10)$$

Substituting for  $k_l$  from equation (6) into (10) and rearranging we obtain,

$$K_{l,OV} = \frac{1}{\frac{1}{k_s} + \frac{1}{E_i} \sqrt{\frac{\pi t}{D_{AB}}}} \quad (11)$$

Moles of carbon-dioxide gas reacted in time 't' is obtained as

$$n_A = A_T \int_0^t N_A dt = A_T (C_{Ai} - 0) \int_0^t K_{l,OV} dt \quad (12)$$

Substituting the expression for  $K_{l,OV}$  into equation (12) and integrating, we obtain

$$n_A = \frac{2A_T C_{Ai} E_a^2 D_A}{\pi} \left\{ \left[ \frac{1}{E_a} \sqrt{\frac{\pi t}{D_A}} \right] \right.$$

$$\left. - \frac{2.303}{k_s} \log \frac{\frac{1}{k_s} + \frac{1}{E_a} \sqrt{\frac{\pi t}{D_A}}}{\frac{1}{k_s}} \right\} \quad (13)$$

Where, the instantaneous enhancement factor,  $E_i$ , is given by

$$E_i = \frac{k_{lr}}{k_l} = \sqrt{\frac{D_A \cdot \lambda}{D_A}} = \sqrt{\pi \lambda t} \quad (14)$$

The average value of the enhancement factor,  $E_a$ , is obtained as

$$E_a = \frac{\int_0^{t_c^*} E_i dt}{t_c^*} = \frac{2}{3} \sqrt{\pi \lambda t_c^*} \quad (15)$$

**2.1.1. Lime solution-CO<sub>2</sub> system.** Since, each mole of carbon-dioxide gas reacts with one mole of calcium hydroxide, the percentage conversion of calcium hydroxide is given by

$$(n_A/n_{B0}) \times 100 \quad (16)$$

Or, Percentage conversion

$$= \frac{2A_T C_{Ai} E_a^2 D_A}{\pi n_{B0}} \left\{ \left[ \frac{1}{E_a} \sqrt{\frac{\pi t}{D_A}} \right] \right.$$

$$\left. - \frac{2.303}{k_s} \log \frac{\frac{1}{k_s} + \frac{1}{E_a} \sqrt{\frac{\pi t}{D_A}}}{\frac{1}{k_s}} \right\} \times 100 \quad (17)$$

**2.1.2. NaOH-CO<sub>2</sub> system.** For this case, one mole of carbon-dioxide reacts with two moles of NaOH. The quantity '2' in equation (14) is replaced by '4' as the percent conversion of sodium hydroxide is given by

$$(2n_A/n_{B0}) \times 100 \quad (18)$$

The above model is for a gas-liquid system. The model predictions have been validated using the experimental data reported by Biswas et al. (1987) for absorption of carbon-dioxide gas from its mixtures with air in a foam matrix made out of sodium-hydroxide solution containing Triton X-100 as a surfactant. Total area  $A_T$  is calculated from a knowledge of number and average size of bubbles at any given time in the foam-bed reactor. The latter in

of bubbles. An expression for its estimation has been proposed by Jana and Bhaskarwar (2010).

The pressure on the inside surface of a bubble is higher by  $2\gamma/R_b$  over that at the convex side of the film. All the bubbles are assumed to be identical and coalescence is neglected.

$$V_b = [V_{b0}^{1/3} + 1.7704\beta \left\{ - \frac{k_s C_A^* \sqrt{\frac{\lambda}{D_A}} \sinh(\sqrt{\frac{\lambda}{D_A}}.a)}{k_s \cosh(\sqrt{\frac{\lambda}{D_A}}.a) + \sqrt{\lambda D_A} \sinh(\sqrt{\frac{\lambda}{D_A}}.a)} t_c \right. \\ \left. + 2k_s \sum_{n=1}^{\infty} \frac{[C_A s_n - C_A^* (s_n + \lambda)] e^{s_n t_c} (k_n \sin k_n a)}{s_n (s_n + \lambda) \left[ \frac{ak_s}{D_A k_n} \sin(k_n a) + \frac{\sin(k_n a)}{k_n} + a \cos(k_n a) \right]} \right\}^3 \quad (19)$$

turn is calculated from the measured volumes

### 3. Experimental

#### 3.1. Bubble volume measurement

Bubble size in the foam column was measured by suction of foam bubbles into a glass tube at approximately 350-360 mm Hg vacuum i.e., nearly 400 mm Hg absolute pressure. A round bottom flask fitted with two stop cocks on its opposite sides were evacuated to this pressure. Two glass tubes of length 0.84 m each were connected to this flask for suction of foam bubbles from the foam column. For measurement of cross-sectional areas, these tubes were filled with water and then drained into a small graduated cylinder. Cross-sectional areas were then calculated from the volume of water collected and the known lengths of tubes. For calculation of bubble sizes, the thickness of the liquid film adhering to the tube surface was neglected and the diameter of bubble in the tube was taken as that of the tube itself.

#### 3.2. Absorption of lean CO<sub>2</sub> in NaOH solution

The details of Experimental procedure has been described by Biswas et al. [19]. However, a

typical method of experiment performed at author's laboratory for a similar work is described here. A known amount of NaOH is dissolved in distilled water to prepare approximately (N/2) solution and required amount of BaCl<sub>2</sub> solution added to precipitate out CO<sub>3</sub><sup>2-</sup> present as impurity. Actual concentration of NaOH solution is determined using standard oxalic acid solution. CO<sub>2</sub> gas mixed with air is passed through an empty bubble column at the desired steady flow rate and 2.50 x 10<sup>-4</sup> m<sup>3</sup> of NaOH solution containing 1640 ppm Triton X-100 is poured into the column. A known foam height is maintained. After the desired time of experiment, the product solution is collected and analyzed using standard HCl solution to determine the conversion.

### 4. Results and Discussion

Predicted values of conversion using the proposed model in this work (equation 16) with the experimental conditions of Biswas et al. [19] are found to agree well with their experimental data (Figure 1). These experiments were also

performed under similar conditions in the author's laboratory and closely matching conversion data have been obtained. However, the work has not yet been communicated for publication.

The prediction of the change of bubble volume with time from the present model (equation 19) for the special case of physical absorption ( $\lambda = 0$ ) in a foam-bed contactor has been compared with the experimental data of Takemura and Yabe [3] who measured the change of size of a carbon-dioxide gas bubble with time during its 'upward movement and dissolution' in water in a bubble column. The bubble-volume change predicted by the theory (equation 19) agrees roughly with the experimental data (Figure 2). Because the bubble experiences a higher turbulence during its upward rise in a bubble column, the rate of dissolution of carbon dioxide from a single bubble is higher than that in a foam-bed contactor. Hence, the observed bubble

volume is lower in a bubble column than that in a foam-bed contactor.

Foam bubble size was also measured in the present work. Measured bubble size agrees closely with that reported in the literature (Table 3). Some photographs of foam bubbles have also been taken and reported elsewhere [17] with mm scales fixed for reference on the column wall. However, because of the cylindrical shape of the column wall and because of refraction, the sizes of bubbles in the photographs appear larger than the actual size.

**Table 1. Correlations for bubble size in bubble column contactors**

Sr No	Investigator(s)	Correlations	Comments
1	Leibson et al.[11]	$d_b = 0.0287d_0^{1/2} Re_0^{1/3}$	$Re_0 < 2100$ ; $d_b$ in m.
2	Kumar and Kuloor [12]	$V_b = (0.976) \frac{(\frac{Q_G}{H_N})^{1.2}}{g^{0.6}}$	Average bubble volume, $m^3$ .
3	Van Krevelen and Hoftijzer [14]	$d_b = [\frac{6\sigma d_0 g_c}{g(\rho_l - \rho_g)}]^{1/3}$	Very low gas flow rate and low viscosity liquids
4	Bhavaraju et al. [13]	$d_b = 3.23(d_0)(\frac{4\rho_l Q}{\pi\mu_l d_0})^{-0.1}(\frac{Q^2}{d_o^5 g})^{0.21}$	Bubble diameter increases with an increase in viscosity of liquid !
5	Van Krevelen and Hoftijzer[14]	$d_b = (\frac{72\rho_l}{\pi^2 g \Delta\rho})^{1/5} Q_{g0}^{0.4}$	For systems other than air-water.
6	Akita and Yoshida [1]	$d_{b,t_0} = d_0(1.88)(u_0 / \sqrt{gd_0})^{1/3}$	Initial diameter of bubbles, single orifice Spurger
7	Akita and Yoshida [1]	$d_b = 26d_c(N_{Bo})^{-0.5}(N_{Ga})^{-0.12}(N_{Fr})^{-0.12}$	Average bubble diameter is a function of column diameter

**Table 2. Specifications of glass tube used for bubble size measurement**

	Volume of water collected (m <sup>3</sup> ) x 10 <sup>6</sup>	Length of tube (m)	Cross-sectional area, (m <sup>2</sup> ) x 10 <sup>4</sup>
Tube I	10.7	0.84	0.1274
Tube II	15.8	0.84	0.188

**Table 3. Bubble size at the slurry-foam interface in a foam column for different superficial gas velocities used in the experiments**

Flow-rate of gas, (m <sup>3</sup> /s) x 10 <sup>4</sup>	Batch No. of sample and solids loading (kg/m <sup>3</sup> )	Cross-sectional area of the tube used, (m <sup>2</sup> ) x 10 <sup>4</sup>	Average length of bubbles sucked into the tube, (m) x 10 <sup>2</sup>	Bubble diameter, (m) x 10 <sup>2</sup>	Bubble diameter (m) x 10 <sup>2</sup> calculated using Kumar and Kuloor (1970) eqn.
1.85	DD2, 20	0.1274	(i) (1.2x4+1.3)/5 = 1.22 (ii) (1.2x3+1.3x2)/5 = 1.24	0.667 0.671	0.67

**Sample calculation**

Equipment and operational parameters and the physico-chemical data (Biswas et al., 1987) used in the calculations are given below:

$$r_c = 3.8 \times 10^{-2} \text{ m}$$

$$Q_G = 5.4 \times 10^{-4} \text{ m}^3/\text{s}$$

$$H_N = 9$$

$$V_l = 1.0 \times 10^{-4} \text{ m}^3$$

$$C_B(0) = 0.84 \times 10^{-3} \text{ g mol/cc} = 0.84 \times 10^{-3} \text{ kmol/lit} = 0.84 \text{ kmol/m}^3$$

$$V_{b0} = (Q_G / H_N)^{1.2} / g^{0.6} = 2.18 \times 10^{-6} \text{ m}^3$$

$$\text{Number of bubbles formed} = (Q_G / V_{b0}) = 248 \text{ s}^{-1}$$

$$\text{Area of bubbles generated} = 248 \times \text{area of each bubble} = 0.1993 \text{ m}^2 / \text{s}$$

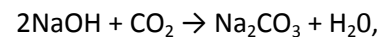
Bubble-rise velocity is assumed to be the same as the superficial velocity ( $V_G$ ) of gas.

$$V_G = 5.4 \times 10^{-4} / [3.14 \times (3.8 \times 10^{-2})^2] = 0.119 \text{ m/s}$$

$$t_c^* = 0.38 / 0.119 = 3.2 \text{ s}$$

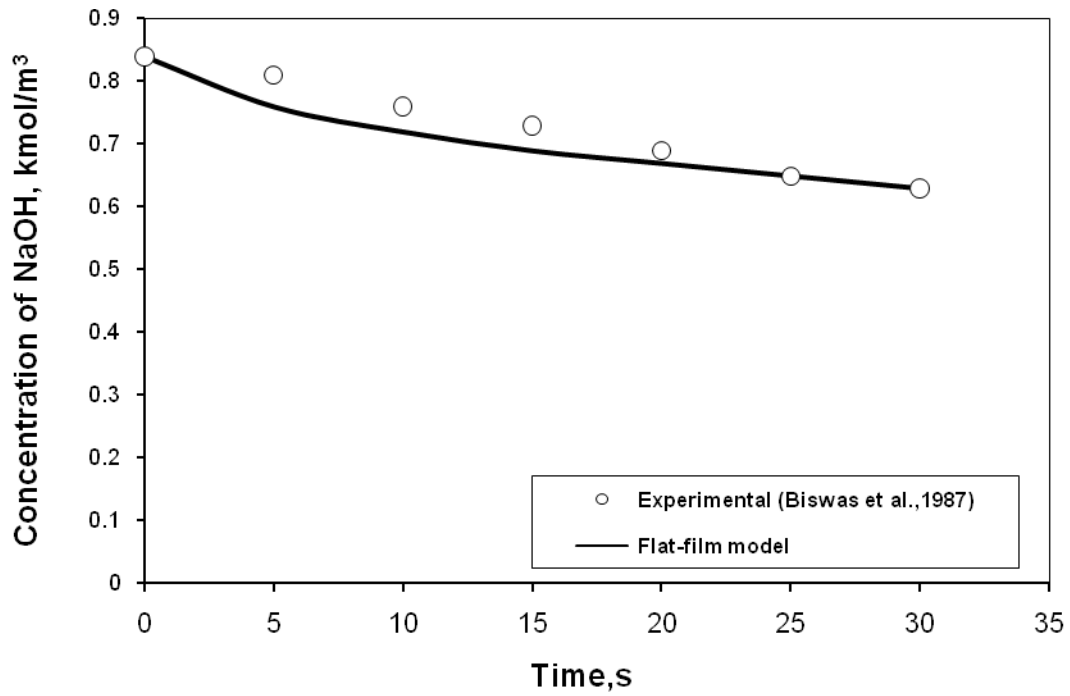
$$n_B(0) = (0.84 \times 10^{-3} \text{ g mol/cc}) \times 100 \text{ cc} = 0.084 \text{ g mol} = 8.4 \times 10^{-5} \text{ kmol}$$

Since each mole of carbon-dioxide gas reacts with two moles of NaOH, as per the reaction

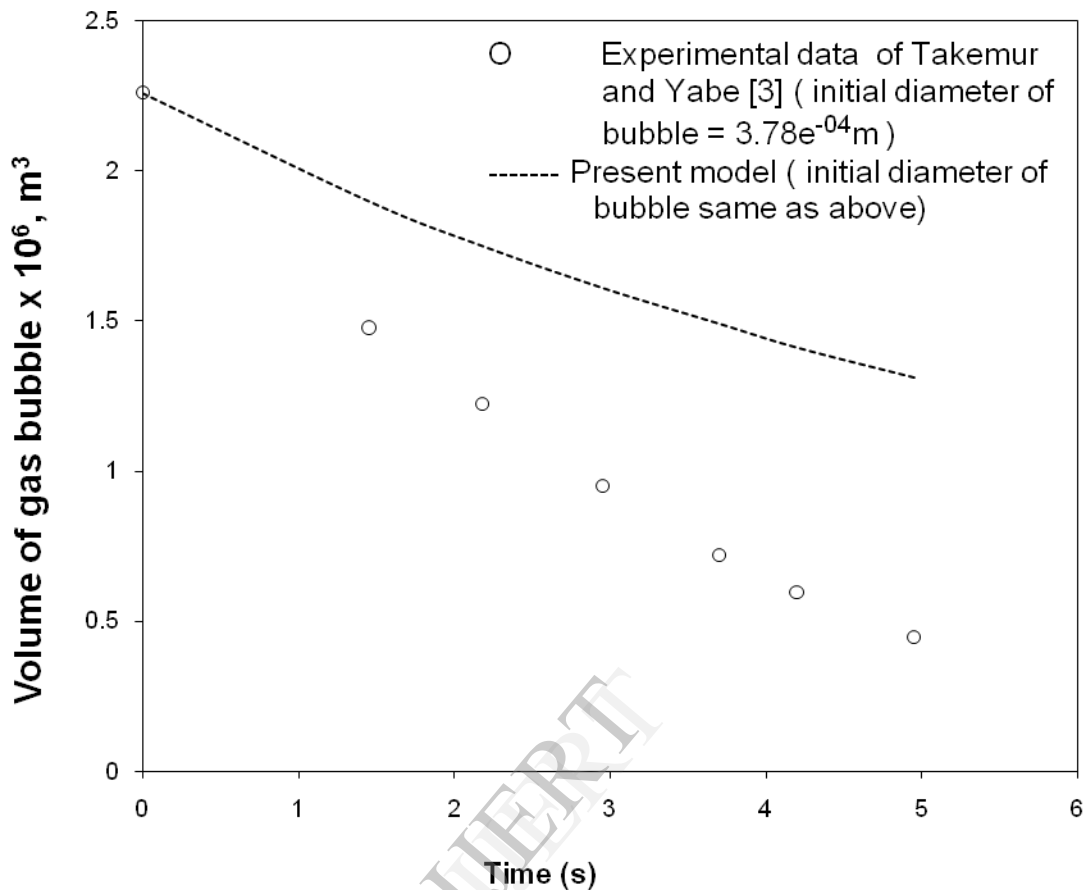


equation (18) along with eqn. (17) are used to calculate the conversion of NaOH.

Comparison of the predictions of flat film model, equations (17 and 18), with the experimental data of Biswas et al. [19] is shown in figure 1.



**Figure 1 Comparison of the flat-film model with the experimental data of Biswas et al. [19]**



**Fig.2. Comparison of bubble volume (Equation 19) with experimental data of Takemura and Yabe [3]**

## Conclusion

Absorption of a lean gas in a foam-bed reactor has been modeled for mass transfer with significant surface resistance. The liquid-phase reactant used in the experiments is the limiting component in the foam section of the foam-bed reactor. The predictions of the model were compared with the experimental data reported in the literature for a gas-liquid foam-bed reactor operated in a semi-batch mode. The

model predictions agreed well with the reported experimental data. Change of bubble volume was predicted from a model reported by the present author. For the special case of physical absorption, the model predictions are found to compare favorably with the experimental data reported in the literature for a single bubble rising in a bubble column.



Bubble size was also determined experimentally.

### Notation

$C_c$	capillary constant, equal to $\sqrt{2\gamma / \rho_l g}$
$d_b$	bubble diameter, m
$d_0$	orifice diameter, m constant, $\text{ms}^{-2}$
$g$	gravitational
$H_N$	number of holes on the orifice
$Q_G$	gas flow rate, $\text{m}^3\text{s}^{-1}$
$r_b$	bubble radius, m
$r_0$	radius of orifice, m
$\Delta\rho$	density difference between gas and liquid, $\text{kg m}^{-3}$
$\rho_G$	density of gas, $\text{kg m}^{-3}$
$\rho_l$	density of liquid, $\text{kg m}^{-3}$
$\mu_l$	viscosity of liquid, $\text{kg m}^{-1}\text{s}^{-1}$
$\theta$	angle of contact at the triple interface
$U_0$	orifice gas velocity, $\text{m s}^{-1}$
$V_b$	bubble volume, $\text{m}^3$

### References

1. Akita, K. and Yoshida, F., 1973, Gas Holdup and Volumetric Mass Transfer Coefficient in Bubble Columns. *Ind. Eng. Chem. Proc. Des. Dev.* **12**(1), 76-80.
2. Calderbank, P. H., 1958, Physical Rate Processes in Industrial Fermentation-Part I: The Interfacial Area in Gas-Liquid Contacting with Mechanical Agitation. *Trans. Instn Chem. Engrs.* **36**, 443-463.
3. Takemura, F. and Yabe, A., 1999, Rising Speed and Dissolution Rate of a Carbon-dioxide Bubble in Slightly Contaminated Water. *J. Fluid Mech.* **378**, 319-334.
4. Treybal, R. E., *Mass-Transfer Operations*, 3<sup>rd</sup> Edition, McGraw-Hill, New Delhi, 1981.
5. Barker, G. S., Jefferson, B. and Judd, S. J., The Control of Bubble Size in carbonated Beverages, 2002, *Chemical Engineering Science*, **57**, 565-573.
6. Datta, R. L., Napier, D. H. and Newitt, D. M., The properties and Behavior of Gas Bubbles formed at a Circular Orifice, Conference on Formation and Properties of Gas bubbles, Meeting of the Institution of Chemical Engineers, Burlington House, London, W.I., Feb 14, 1950.
7. Painmanakul, P., Wachirasak, J., Jamnongwong, M. and Hebrad, G., 2009, Theoretical Prediction of Volumetric Mass Transfer Coefficient ( $K_a$ ) for Designing an aeration tank, *Engineering Journal*, **13**(3), 13-28.
8. Kantarci, N., Borak, F., Ulgen, K.O., 2005, Bubble Column Reactors, *Process Biochemistry*, **40**, 2263-2283.
9. Moo-Young, M., Blanch, H. W., 1981, Design of Biochemical Reactors, *Adv Biochem Eng*, **19**, 1-69.
10. Miller, D. N., 1974, Scale-up of Agitated Vessels gas-Liquid Mass Transfer, *AIChE J*, **20**, 445-453.
11. Liebson, I., Halcomb, E.G., Cacosco, A.G., Jamie, J. J., 1956, Rate of Flow and Mechanics of Bubble Formation from Single Submerged Orifices, *AIChE J*, **2**(3), 296-306.
12. Kumar, R. and Kuloor, N. R., *Advances in Chemical Engineering*, Vol. 8, p. 286. Academic Press, New York 1970.
13. Bhavajaju, S. M., Mashelkar, R. A., Blanch, H. W., 1978, Bubble Motion and Mass Transfer in non-Newtonian Fluids, *AIChE J*, **24**, 1063-76.
14. Van Krevelen, W. and Hoftijzer, P.J., 1950, *Chem. Eng. Prog.*, **46**(1), 29.
15. Wilkinson, P. M., Haringa, H. and Dierendonck, L. L.V., 1994, Mass Transfer and Bubble Size in a Bubble Column Under Pressure, *Chemical Engineering Science*, **49** (9), 1417-1427.
16. Hebrad, G., 1995, Etude de l'influence du distributeur de gaz sur l'hydrodynamique et le transfert de matiere gaz-liquide des colonnes a bbulles, INSA, Toulouse.
17. Jana, S.K., and Bhaskarwar A. N., 2010, Modeling Gas Absorption Accompanied By Chemical Reaction In Bubble Column And Foam-Bed Slurry Reactors, *Chemical Engineering Science*, **65**, 3649-3659.

18. Biswas, J., and Kumar, R., 1981, Mass Transfer with Chemical Reaction in A Foam-Bed Contactor, *Chem. Eng. Sci.*, 36, 1547-1556.
19. Biswas, J., Kumar, R. and Asolekar, S. R., 1987, Effect of Surface Resistance Arising Due to Surfactant on Gas Absorption Accompanied By A Chemical Reaction in A Foam-Bed Reactor, *Can. J. Chem. Eng.*, 65, 462-469.
20. Sharma, R. K., Gaikwad, A. and Bhaskarwar, A.N., 2005, Mass Transfer with Chemical Reaction and Desorption in a Foam-bed Reactor. *Chem. Eng. Comm.* **192**, 597-619.
21. Jackson, J., 1963, Gas Cleaning by the Foam Method, *Brit. Chem. Engng.* **8**(5), 319-321.
22. Bhaskarwar, A. and Kumar, R., 1984, Oxidation of Sodium Sulphide in A Foam-Bed Contactor, *Chem. Eng. Sci.*, 39, 1392-1399.

IJERT