

GAS HOLDUP AND $k_L a$ IN PERFORATED-PLATE BUBBLE COLUMNS IN THE PRESENCE OF SOLID PARTICLES

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The effect of solid particles on values of volumetric liquid-side mass transfer coefficient, $k_L a$, and gas holdup, ε_G , was determined in a bubble column 0.14 m in diameter within the range of solid phase concentration $c_s = 0-10\%$ (mass). Experiments were carried out in air-water system at zero liquid flow rate, glass spheres of average diameters 24, 36, 50, 102, 142, 190, and 280 μm and fine ZnO powder (average particle size 2.3 μm) were used as a solid phase. Perforated plate with holes diameter 1.6 mm and free plate area 0.2% was used for gas distribution, superficial gas velocities ranged between 0.036 and 0.215 m/s. Only negative effect of the of gas holdup and $k_L a$ was observed in the whole range of experimental conditions, this effect being most pronounced in the region of small particle sizes ($d_s \leq 36 \mu\text{m}$).

Bubble column reactors have been widely used for reactions in systems gas-liquid-suspended solid phase where the solid phase can be a catalyst, one of the reaction components or a reaction product. Decisive hydrodynamic and mass transfer characteristics of bubble reactors for such systems include holdup ratios, interfacial areas and mass transfer coefficients, and mixing characteristics of individual phases. Despite a considerable number of studies devoted in last few years to reactors of this type, a complex evaluation of the effect of solid phase parameters (solid phase concentration, size and shape of solid particles) on hydrodynamics and mass transfer in aerated slurries is still missing.

It has been commonly accepted that the presence of solid phase influences significantly the rate of mass transfer between gaseous and liquid phase in bubble column reactors. Good qualitative agreement can be observed between data of numerous authors^{1-3,7} reporting negative effect of solid particles at high solid phase concentrations. Significant increase of suspension viscosity and ceasing of turbulence in the bed observed under such conditions can be apparently responsible for the increase of bubble coalescence rate and for the formation of large bubbles with high ascension rate and thus consequently for decrease of gas holdup as well as of the gas-liquid interfacial area. In concentrated suspensions of extremely small particles ($d_s < 3 \mu\text{m}$) further decrease of effective gas-liquid interfacial area can occur due to the presence of solid particles at the interphase⁴.

In opposition to majority of works describing only hindering effect of solid particles on the rate of gas-liquid mass transfer several cases of facilitated gas absorption in suspensions have

been also reported. Theoretically, the existence of such phenomenon seems to be justifiable only in suspensions with relatively low solid phase concentration while the negative solid particles effects discussed above are always predominant in concentrated suspensions. Beside the way of phases contacting, concentration of particles, their size and density and in some special cases even the adsorption activity of particle surface has to be taken into consideration. The enhancement of gas-liquid mass transfer in aerated suspensions can be ascribed to disturbances of interfacial area and to the increase of induced microscale turbulence at the interphase due to interactions of solid particles with gas bubbles. Collisions of bubbles with solid particles having large inertial moment can cause significant bubble deformations and consequently spur break up of bubbles and interphase renewal. It follows from theory that the existence of such phenomena has been limited to the region defined by relation^{1,5}

$$We_{crit} = \rho_s d_s v_B^2 / \sigma \leq 3, \quad (1)$$

where v_B denotes the relative velocity of gas bubbles to solid particles. For spherical glass particles with characteristic diameter $d_s = 100 \mu\text{m}$ critical value of Wever number, $We = 3$, corresponds to $v_B = 0.2-0.3 \text{ m/s}$.

The enhancing effect of solid particles was observed *e.g.* by Sittig⁶ in a stirred fermentor 1 m in diameter. Addition of solid granulate ($d_s = 3 \text{ mm}$, $\rho_s = 1410 \text{ kg/m}^3$, $c_s = 2\%$) caused about 20% increase of $k_L a$. Similarly Joosten and coworkers⁷ reported 15% increase of $k_L a$ in a stirred bubble cell due to addition of small amount of glass or polypropylene particles ($d_s = 53-250 \mu\text{m}$). Miyauchi and coworkers⁴ observed positive effect of solid phase even in the region of extremely small particles. Mass transfer facilitation can occur also in cases when solid particles exhibit high adsorption activity and their size is comparable with the effective thickness of liquid film at the gas-liquid interphase. For such cases Alper, Wichtendahl and Deckwer⁸ postulated a simple transport mechanism according to which solid particles may move into the concentration boundary at the interphase, adsorb gas for some time there and then go back the depth of liquid phase to desorb it.

In our work fundamental bubble bed parameters, $k_L a$ and gas holdup, were studied in aerated suspension of inert solid particles of different size. It was the aim of our study to determine behaviour of such system under conditions of stable uniform bubble bed aeration and to obtain experimental evidence on the effect of particles size and concentration on the rate of mass transfer between gas and liquid phase and consequently on the $k_L a$ values.

EXPERIMENTAL

Equipment and Experimental Conditions

Experimental set-up is shown schematically in Fig. 1. The single-stage bubble column used for experiments was made of perspex, column diameter was 0.142 m. Experiments were carried out at zero liquid flow rate with water and air as liquid and gaseous phase respectively. Seven fractions of spherical glass particles (mean fractions diameters 24–315 μm) and finely powdered ZnO (average particle size 2.3 μm) were used as a solid phase, all fractions used are listed in Table I. Fractions G4–G7 were classified by screen analysis, fractions G1–G3 were separated by flotation using dimethylphthalate as a liquid carrier. Appropriate values of average particle diameter for individual fractions were obtained by sample analysis on Texture analysis system Leitz.

Superficial gas velocity was varied between 0.036 and 0.215 m/s. Experiments were performed at constant liquid phase volume, the ratio of clear liquid height to column diameter (H_0/D_K) was equal to three in all experimental runs. Low value of H_0/D_K ratio was chosen to reduce axial dispersion of solid phase and thus to ensure a uniform particles distribution in the bed. It was also proved previously that the assumption of complete liquid phase mixing used in evaluation of $k_L a$ data from dynamic absorption experiments was always fulfilled for $H_0/D_K \leq 5$.

Stainless-steel perforated plate of thickness 0.003 m was used as a gas distributor. Geometrical parameters of the plate (hole diameter, d_0 , free plate area ratio, ϕ) were chosen regarding following requirements: 1) Stability of turbulent bubbling regime in the whole range of experimental

TABLE I
Summary of used solid particles

Solid phase	Key	Mesh size μm	Mean size μm
Glass sphere	G ₁		24.4
	G ₂		35.7
	G ₃		49.6
	G ₄	80–125	101.6
	G ₅	120–160	142.1
	G ₆	185–200	190.4
	G ₇	250–315	280.2
Zinc oxide	Z ₁		2.3

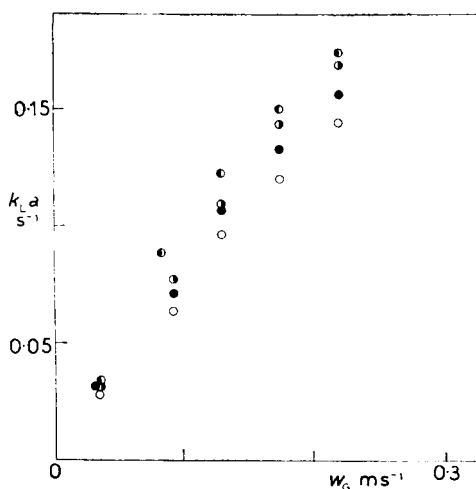


FIG. 1
Dependence of $k_L a$ on w_G for spherical glass particles G4 ($d_0 = 102 \mu\text{m}$) at various solid phase concentrations c_s , mass %: $\circ$ 0, $\bullet$ 2.5, $\bullet$ 5, $\circ$ 10

conditions (see Zahradnik and Kašánek¹⁶). Homogeneous ("foam-like") bubbling regime was observed in our former studies¹⁶⁻¹⁸ on plates with small diameter holes at low medium gas flow rates. Such bubbling regime was however unstable at high gas throughputs and transition to the regime of turbulent bubbling occurred with increasing gas flow rate. Correspondingly, dependences of $k_L a$ and gas holdup on superficial gas velocity exhibited a maximum corresponding to fully developed homogeneous bubbling regime followed by subsequent decrease of $k_L a$ and ε_G data in the transition region. Formation of homogeneous bubble bed was therefore to be avoided in this work to obtain unambiguously interpretable evidence on the solid phase effect in the whole range of gas flow rates.

2) Uniform distribution of holes on the whole plate area and a sufficient concentration of holes on the plate preventing sedimentation of solid particles on the plate surface.

3) Stable uniform gas distribution (*i.e.* all plate holes opened for passage of gas) in the whole range of experimental conditions. Gas flow rate corresponding to the onset of such distributing plate performance can be estimated (for a specific gas-liquid system and plate geometry) from the critical value of Weber number proposed by Merseman and coworkers⁹

$$We_{0,crit} = u_2^{0,crit} d_0 \rho_G / \sigma = 2. \quad (2)$$

To ensure stable uniform gas distribution, condition $We_0 \geq We_{0,crit}$ has to be therefore fulfilled in the whole region of gas throughputs.

Distributing plate parameters were chosen to comply with all requirements discussed above. Free plate area was 0.2% and holes diameter 0.0016 m. Drilled holes were distributed uniformly over the whole plate area in a triangular pitch.

Experimental program included determination of dependences of $k_L a$ and ε_G on gas flow rate at various solid phase concentrations and particle diameters. Values of $k_L a$ and ε_G were measured at five gas flow rates within the range of superficial gas velocities 0.036–0.216 m/s. Experiments were performed at solid phase concentrations 0; 0.625; 1.25; 2.5; 5; and 10% (mass) with eight particles fractions, average fraction diameters ranged between 2.3 and 315 μm (Table I). Complete set of experiments performed on all levels of w_G , c_S , and d_S yielded 240 values of $k_L a$ and ε_G respectively.

Determination of gas holdup and $k_L a$. Bubble bed expansion method was used for gas holdup determination. The height of aerated bed was determined visually from the position of polystyrene-ring float. The dynamic method was applied for $k_L a$ measurement based upon monitoring of the unsteady oxygen absorption into previously deoxygenized water in the bed *i.e.* on the evaluation of a system response to an input step change nitrogen – air. The Clark-type fast-response polarographic electrode with a membrane of fluorinated polypropylene (thickness 0.025 mm) was used for measurement of dissolved oxygen concentration. The normalized electrode response $G(t)$ to an arbitrary change of oxygen concentration $C(t)$ can be described by a relation proposed by Linek and coworkers¹⁰

$$G(t) = \int_0^t \frac{dG^1(t-\tau)}{d\tau} C(t) d\tau, \quad (3)$$

where $G^1(t)$ is a transient electrode characteristics which can be determined by a procedure developed by Linek and coworkers^{11,12}. The oxygen electrode dynamics was described by the two-regional model proposed by Linek and Beneš¹¹. The time dependence of oxygen concentration $C(t)$ was expressed according to model of Dang, Karrer, and Dunn¹³ based upon oxygen balance in liquid and gaseous phase. Experimental electrode response was then compared with the

response calculated from the convolution integral (3) and appropriate $k_L a$ values were searched for using a numerical optimization method.

RESULTS AND DISCUSSION

To check the reproducibility of experimental methods used in our work, values of gas holdup and $k_L a$ corresponding to gas-liquid bed at zero solid phase concentration ($\varepsilon_G^0, k_L a^0$) were determined in all experimental runs. It was found that the shape of nonlinear dependences $k_L a$ vs w_G obtained in l-g-s systems was similar to that observed for the two-phase air-water system in the turbulent bubbling region. As an illustration, $k_L a$ data obtained for fraction G4 are plotted in Fig. 1 against superficial gas velocity, w_G . Only negative effect of the solid phase on $k_L a$ values was observed in these experiments as can be seen from the graph where all experimental points lie under the limiting curve corresponding to air-water system. Relative deviations between $k_L a$ values for gas-liquid-solid and gas-liquid systems defined as

$$(\Delta k_L a)_{rel} = ((k_L a^0 - k_L a)/k_L a^0) \cdot 100, \quad (4)$$

were lower or equal to 20% for fraction G2-G7 and up to 33% for fraction G1. While the absolute differences of $k_L a$ values due to the presence of solid phase ($k_L a - k_L a^0$) increased with increasing gas flow rate relative deviations $(\Delta k_L a)_{rel}$ decreased with increasing w_G . As can be seen from data ε_G vs w_G for fraction G4 which are plotted in Fig. 2, character of such dependence was similar to curves $k_L a$ vs w_G . Relative deviations of gas holdup values

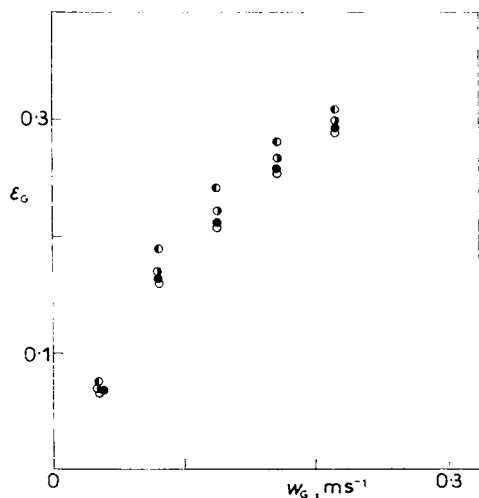


FIG. 2

Dependence of gas holdup on w_G for spherical glass particles G4 ($d_s = 102 \mu\text{m}$) at various solid phase concentrations c_s , mass %:
 ○ 0, ◐ 2.5, ● 5, ○ 10

$$\Delta \varepsilon_{G,rel} = ((\varepsilon_G - \varepsilon_G^0)/\varepsilon_G^0) \cdot 100 \quad (5)$$

did not exceed 20% for fractions G1–G7 (except for the values corresponding to the lowest gas flow rate, $w_G = 0.036$ m/s). Similarly as data $(\Delta k_{La})_{rel}$, values $\Delta \varepsilon_{G,rel}$ decreased steadily with increasing gas flow rate for all solid phase fractions. It can be said generally that for all particle fractions addition of solid phase influenced negatively values of gas holdup and k_{La} in comparison with corresponding data for two-phase (air–water) system. No significant positive effect of solid particles presence on values of ε_G and k_{La} was observed within the whole range of our experimental conditions. In the case of largest particles (fraction G7) fast decrease of k_{La} and ε_G occurred in the range of solid phase concentrations $c_s = 0 - 1.25\%$ (mass) while further increase of c_s up to 10% exhibited practically no influence on k_{La} and ε_G values. On the other hand continuous decrease of both k_{La} and ε_G data was observed for fraction G4 in the whole range of solid phase concentrations (Fig. 3).

The effect of finely powdered ZnO on gas holdup and k_{La} values proved to be more significant in comparison with that of spherical glass particles discussed above, negative effect of ZnO addition was clearly apparent already at low concentration 0.625% (mass). Values of k_{La} decreased with increasing solid phase concentration to 40% of the value corresponding to air–water system (Fig. 4), values of gas holdup to 70% of ε_G^0 (Fig. 5). In the whole range of ZnO concentrations dependences $(\Delta k_{La})_{rel}$ vs w_G went through maxima at low gas flow rates with subsequent decrease at $w_G \geq 0.08$ m/s. In Fig. 6 k_{La} data are plotted against ZnO concentration for various superficial gas velocities. As can be seen from the figure, strongly decreasing dependences k_{La} vs c_s were obtained at all gas flow rates.

It has been apparent from above presented results that the effect of particle size on ε_G or k_{La} was of minor importance for particles larger than 50 μm . Significant dependences of k_{La} on d_s were observed only in experiments with particles of small size i.e. with fractions G1, G2, G3 and with ZnO. The particle diameter effect is illustrated in Fig. 7 for solid phase concentration $c_s = 5\%$. Clearly apparent decrease of k_{La} with d_s can be observed at small d_s values. No conclusive evidence of such effect was however obtained at lower solid phase concentrations ($c_s < 5\%$) where differences between k_{La} data corresponding to individual particle fractions were comparable with accuracy limits of the measuring method. Mutual relations between individual solid phase fractions are well apparent in Fig. 8 in which data k_{La} vs w_G are plotted for all particle fractions ($c_s = 5\%$ mass). Apparently dependences k_{La} vs w_G can be fitted by a single curve for all particle diameters larger than 50 μm with accuracy $\pm 5\%$. Similarly a single unambiguous functional relation $\varepsilon_G = \varepsilon_G(w_G)$ can be used for gas holdup data correlation at $d_s \geq 25 \mu\text{m}$.

Experimental data ε_G vs w_G were correlated by the relation

$$\varepsilon_G = w_G / (P + Q \cdot w_G) \quad (6)$$

commonly used for gas-liquid systems. In Eq. (6), coefficient P characterizes the pattern of liquid phase circulation in bubble bed while the value of coefficient P depends on gas-liquid system properties. Values $Q = 2$, $P = 0.18$ m/s were presented for air-water system by Reith¹⁴ while Mashelkar¹⁵ obtained values $Q = 2$ and $P = 0.30$ m/s by processing an extensive set of experimental data of various authors. Our gas holdup data obtained in the presence of suspended solid phase were correlated either by the general two-parameter equation (6) or by the simplified relation (7) obtained from Eq. (6) by substitution for coefficient Q ($Q = 2$)

$$\varepsilon_G = w_G / (P + 2w_G). \quad (7)$$

Correlation accuracy was estimated from values of statistic residue. Comparison of results proved that only insignificant improvement of correlation accuracy was achieved by transition from the single parameter Eq. (7) to the two-parameter relation (6). No difference in correlation accuracy was observed between the two-phase and three-phase systems. For glass spheres fractions G2-G7 coefficient P

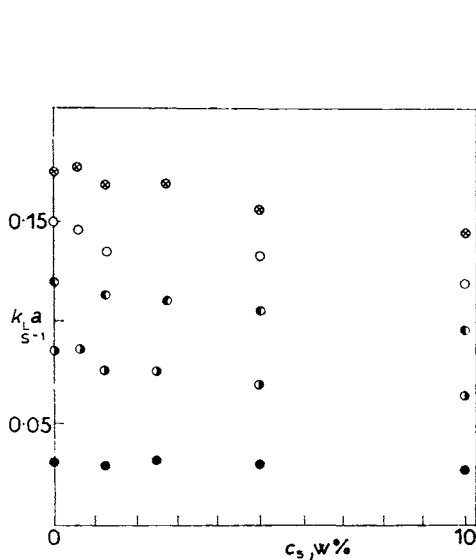


FIG. 3

Dependence of $k_L a$ on c_s for fraction G4 ($d_s = 102 \mu\text{m}$) at various superficial gas velocities w_G , m s^{-1} : $\bullet$ 0.0361, $\blacksquare$ 0.0812, $\blacklozenge$ 0.126, $\circ$ 0.171, $\otimes$ 0.216

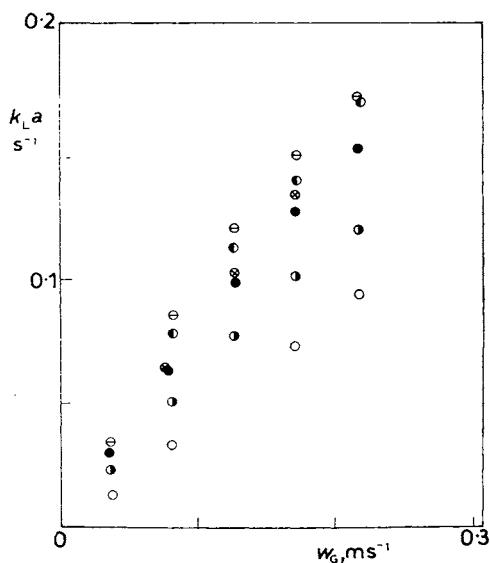


FIG. 4

Dependence of $k_L a$ on w_G for finely powdered ZnO ($d_s = 2.3 \mu\text{m}$) at various solid phase concentrations c_s , mass %: $\circ$ 0, $\bullet$ 0.625, $\otimes$ 1.25, $\blacklozenge$ 2.5, $\blacksquare$ 5, $\circ$ 10

was independent of particle size in the whole range of experimental conditions and its dependence on c_s was well described by the exponential relation

$$P = 0.29 + 0.031 \cdot c_s^{0.45}. \quad (8)$$

Experimental data $\varepsilon_G - w_G$, $k_L a - w_G$, and $k_L a - \varepsilon_G$ were further correlated by exponential-type relations

$$\varepsilon_G \approx w_G^{r1}, \quad k_L a \approx w_G^{r2}, \quad k_L a \approx \varepsilon_G^{r3} \quad (9-11)$$

where $r2 = r1 \cdot r3$.

In Fig. 11 $k_L a$ data for air-water system and for systems with glass spheres ($d_s = 102 \mu\text{m}$, $c_s = 10\%$) and with ZnO ($c_s = 10\%$) were plotted in logarithmic co-ordinates against w_G . Correlation of data for air-water system yielded value of exponent $r2$, $r2 = 0.877$ which agreed well with results reported previously by Deckwer and coworkers¹⁷ ($r2 = 0.884$) or by Zahradník and coworkers^{26,18} ($r2 = 0.85$). With increasing deviations from two-phase system behaviour, values $r2$ increased

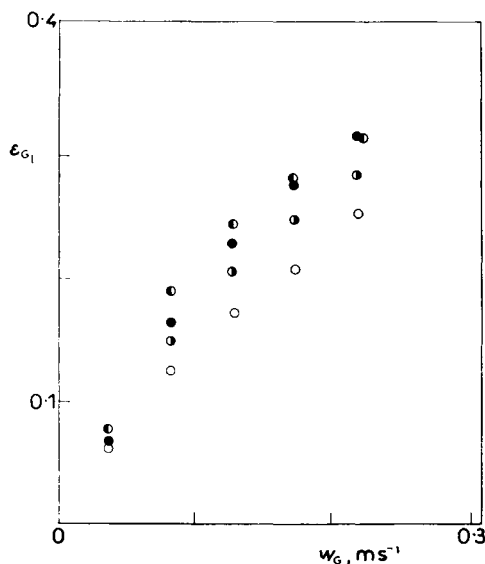


FIG. 5

Dependence of gas holdup on w_G for finely powdered ZnO ($d_s = 2.3 \mu\text{m}$) at various solid phase concentrations c_s , mass %: $\circ$ 0, $\bullet$ 2.5, $\circ$ 5, $\circ$ 10

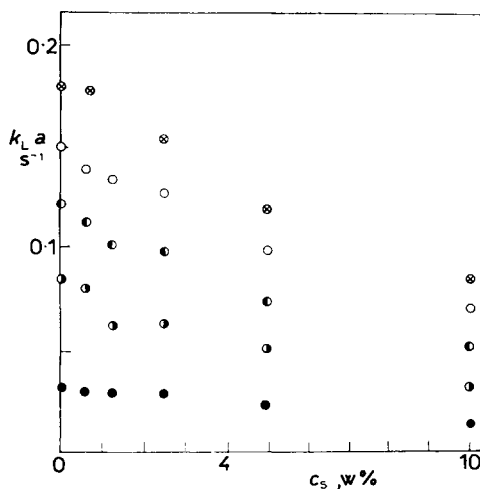


FIG. 6

Dependence of $k_L a$ on c_s for finely powdered ZnO ($d_s = 2.3 \mu\text{m}$) at various superficial gas velocities w_G , m s^{-1} : $\bullet$ 0.0361, $\circ$ 0.0812, $\circ$ 0.126, $\circ$ 0.171, $\times$ 0.216

up to $r_2 = 1.05$ corresponding to aerated suspension of ZnO. Apparently thus, dependences $k_L a$ vs w_G were almost linear in concentrated suspensions. Under such conditions relatively better fit of experimental data was achieved in comparison with systems exhibiting strongly nonlinear dependence $k_L a$ vs w_G . Indeed this should be born in mind when considering data correlation in wide range of experimental conditions.

Relation between experimental data of $k_L a$ and gas holdup was independent of particles size and concentration for $d_s > 36 \mu\text{m}$ and it was identical with that for two-phase (air–water) system. As an illustration, experimental dependence $k_L a$ vs ε_G obtained in system with glass spheres (fraction G4) in the whole range of c_s is shown in Fig. 9. As can be seen all experimental data lie on a single curve with small scatter. Identical shape of dependence $k_L a$ vs ε_G can be observed also in Fig. 10 summarizing experimental data obtained in air–water system and in three phase systems with individual glass spheres fractions (G1–G7) or with ZnO at constant solid phase concentration, $c_s = 10\%$ (mass). In the whole experimental range of solid phase concentrations ($c_s = 0–10\%$) r_3 value was constant and practically identical with that for air–water system, $r_3 = 1.33$. The systems were thus sufficiently defined by relation $k_L a - w_G$. For small glass particles ($d_s \leq 36 \mu\text{m}$) such a generalized

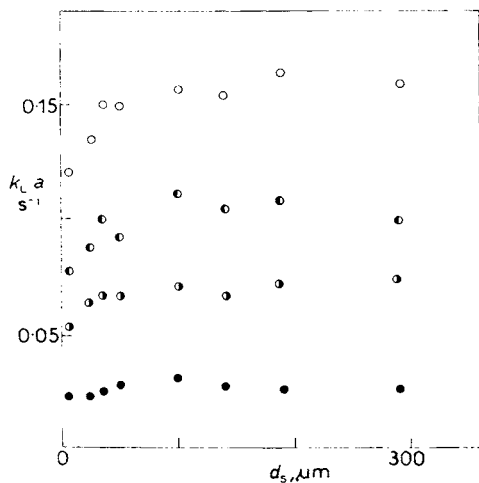


FIG. 7

Dependence of $k_L a$ on particle diameter, d_s , at various superficial gas velocities; $c_s = 5\%$ mass w_G , m s^{-1} : ● 0.0361, ○ 0.812, ○ 0.126, ○ 0.216

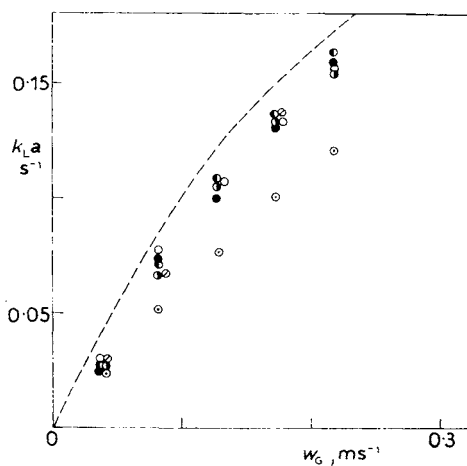


FIG. 8

Dependence of $k_L a$ on w_G for various particle sizes; $c_s = 5\%$ mass; spherical glass particles: $d_s \mu\text{m}$: ○ 50, ○ 102, ○ 142, ○ 190, ● 280; powdered ZnO: $d_s \mu\text{m}$: ○ 2.3

approach cannot be however applied as the dependences $k_L a$ vs ε_G were strongly dependent on solid phase concentration. Assuming only insignificant differences between k_L values for different gas-liquid or gas-liquid-solid systems, ratio of gas holdup to bubble size (represented by Sauter mean diameter, D_{St}) and consequently the interfacial area defined as $a = 6\varepsilon_G/D_{St}$ have to be constant in all systems which can be correlated by a single relation $k_L a = k_L a(\varepsilon_G)$. Identical bubble bed structure can be observed in all such systems under turbulent bubbling conditions. The fact that character of dependence $k_L a - \varepsilon_G$ changed significantly at certain boundary value of particle size seems therefore to support our assumption that unlike the segregated systems containing large coarsely dispersed solid particles, suspensions of small finely powdered particles can be considered as a continuum with specific physical properties. Apparently the characteristic hydrodynamic behaviour of such systems influences negatively values of both k_L and interfacial area a . In suspensions of extremely small (microscale) particles (as was the case of ZnO) additional negative effect of interfacial area blocking can be also considered.

Beside purely empirical exponential-type relations presented above (Eqs (9)–(11)) some theoretically based relations can be also used for calculation of decisive bubble

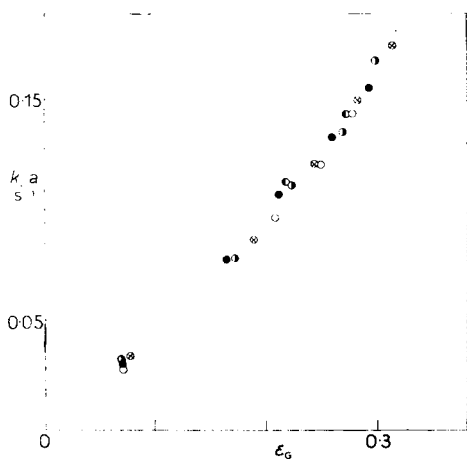


FIG. 9

Dependence of $k_L a$ on gas holdup for spherical glass particles G4 ($d_s = 102 \mu\text{m}$) at various solid phase concentrations c_s , mass %:
 ○ 0, ● 1.25, ◐ 2.5, ◑ 5, ◒ 10

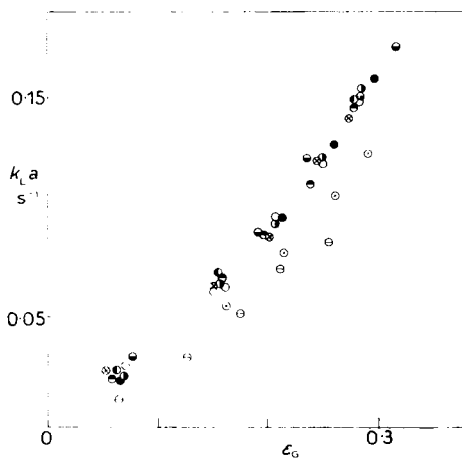


FIG. 10

Dependence of $k_L a$ on gas holdup for various particle sizes; $c_s = 10\%$ mass; spherical glass particles: d_s , μm : ○ 24, ● 36, ◐ 50, ◑ 102, ◒ 142, ◓ 190, ◔ 280; powdered ZnO: d_s , μm : ◕ 2.3; water ◑

bed characteristics. Applying the Komogorov's concept of isotropic turbulence to the liquid phase of a bubble bed, Kaštánek¹⁹ derived a relation for $k_L a$ in the shape

$$k_L a = K \cdot w_G^{0.65} \cdot \varepsilon_G^{0.35} (1 - \varepsilon_G)^{0.65}, \quad (12)$$

where K is a lumped parameter characterizing gas-liquid system properties. In our present work an attempt was made to apply this relation even for correlation of $k_L a$ data in systems with suspended solid phase. In Fig. 12 data of $k_L a$ for air-water system and for l-g-s systems with fraction of glass spheres G4 and with ZnO (at constant solid phase concentration, $c_s = 10\%$) are plotted against the term of the right side of Eq. (12), $(w_G^{0.65} \cdot \varepsilon_G^{0.35} (1 - \varepsilon_G)^{0.65})$. As can be seen from the graphical presentation, the dependences were linear for all three systems. Value of coefficient K obtained from the graph for air-water system, $K = 0.048$ (for w_G in cm/s) was higher than the value reported previously by Kaštánek¹⁹, $K = 0.028$. It is apparent from Fig. 12 that relation (12) is valid even for gas-liquid-solid systems exhibiting strong deviations from behaviour of two-phase gas-liquid systems.

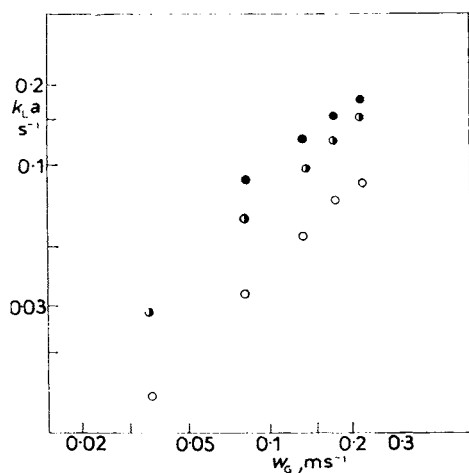


FIG. 11

Dependence of $k_L a$ on w_G for selected systems: ● water; ● spherical glass particles, $d_s = 102 \mu\text{m}$, $c_s = 10\%$ mass; ○ powdered ZnO, $d_s = 2.3 \mu\text{m}$, $c_s = 10\%$ mass

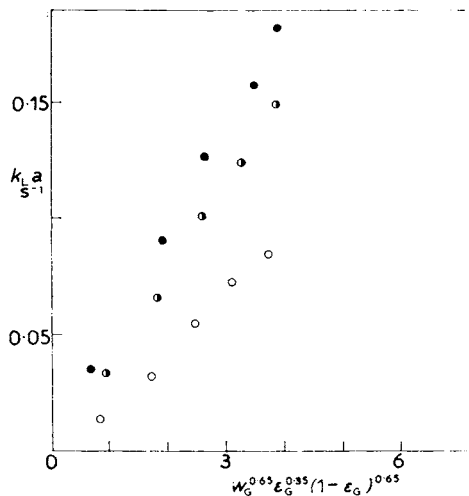


FIG. 12

Dependence of $k_L a$ on the term $(w_G^{0.65} \cdot \varepsilon_G^{0.35} \cdot (1 - \varepsilon_G)^{0.65})$: ● water; ● spherical glass particles, $d_s = 102 \mu\text{m}$, $c_s = 10\%$ mass; ○ powdered ZnO, $d_s = 2.3 \mu\text{m}$, $c_s = 10\%$ mass

CONCLUSION

Only negative effect of the presence of solid phase on values of gas holdup and $k_L a$ in gas-liquid-solid systems was observed within our experimental conditions, in comparison with data for gas-liquid systems. This effect was relatively small and independent of particle size for particles of diameter larger than $36\text{ }\mu\text{m}$, while a steady decrease of both $k_L a$ and ε_G with decreasing particle size was apparent in the range of smaller particle diameters ($d_s \leq 36\text{ }\mu\text{m}$). The largest decrease of $k_L a$ and ε_G values in comparison with the two-phase air-water system was observed in experiments in which finely powdered ZnO (average particle size $2.3\text{ }\mu\text{m}$) was used as a solid phase. In such a case $k_L a$ equaled to 40% and ε_G to 70% of corresponding values obtained for air-water system.

LIST OF SYMBOLS

a	interfacial area related to a unit of liquid phase volume
c_s	concentration of solid phase in suspension (% mass)
C	concentration of oxygen dissolved in liquid phase
d_0	plate hole diameter
d_s	diameter of solid particles
D_K	column diameter
H_0	height of clear liquid in bubble bed
$k_L a$	volumetric liquid-side mass transfer coefficient
t	time
We_0	Weber number related to plate hole diameter $We_0 = u_0^2 d_0 \rho_G / \sigma$
w_G	superficial gas velocity
u_0	linear gas velocity in plate holes
ε_G	gas holdup
ρ_G	gas phase density
ρ_s	solid phase density
φ	relative free plate area
σ	interfacial tension

REFERENCES

1. Kürten H., Zehner P.: *Ger. Chem. Eng.* 2, 220 (1979).
2. Deckwer W.-D., Alper E.: *Chem.-Ing.-Tech.* 52, 219 (1980).
3. Slessor C. G. M., Allen W. T., Cuning E. R., Pawlowski V., Shields J.: *ESCRE 4*, Brussels 1968, Supplement of *Chem. Eng. Sci.*, p. 41–45.
4. Miyauchi M., Yguchi A., Uchida S., Koide K.: *Can. J. Chem. Eng.* 59, 640 (1981).
5. Lee J. C., Sherrard A. J., Buckley P. S.: *Proc. Int. Symp. Fluidisation*, Toulouse 1973.
6. Sitting W.: *Verfahrenstechnik* 11, 73 (1977).
7. Joosten G. E. H., Schilder J. G. M., Jansen J.: *Chem. Eng. Sci.* 32, 564 (1977).
8. Alper E., Wichtendahl B., Deckwer W.-D.: *Chem. Eng. Sci.* 35, 217 (1980).
9. Mersmann A.: *Ger. Chem. Eng.* 1, 1 (1978).

10. Linek V., Beneš P., Vacek V.: *Ind. Eng. Chem. Fundam.* **18**, 240 (1979).
11. Linek V., Beneš P.: *Biotechnol. Bioeng.* **19**, 741 (1977).
12. Linek V., Beneš P., Hovorka F., Vacek V.: *This Journal* **43**, 2980 (1978).
13. Dang N. D. P., Karrer D. A., Dunn I. J.: *Biotechnol. Bioeng.* **19**, 853 (1977).
14. Reith T.: *Thesis*. T. H. Delft 1968.
15. Mashelkar R. A.: *Brit. Chem. Eng.* **15**, 1297 (1970).
16. Zahradník J., Kaš tánek F.: *Chem. Eng. Commun.* **3**, 413 (1979).
17. Deckwer W.-D., Burckhart R., Zoll G.: *Chem. Eng. Sci.* **29**, 2177 (1974).
18. Zahradník J., Kratochvíl J., Kaš tánek F., Rylek M.: *Chem. Eng. Commun.* **15**, 27 (1982).
19. Kaš tánek F.: *This Journal* **42**, 1494 (1977).