Organic Liquids in a Bubble Column: Holdups and Mass Transfer Coefficients

Gas holdups and volumetric mass transfer coefficients k_La are studied in a bubble column of 0.095 m dia. with 50 different gas-liquid systems comprising pure and mixed organic liquids and various gases. The gas holdups measured in pure organic liquids can be represented by existing correlations but the values in liquid mixtures are high. On the other hand, all mass transfer coefficients can be correlated uniformly by a new dimensionless equation, with 13.3% mean error.

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Introduction

Bubble columns are widely used in the chemical industries as fermentors, absorbers, and reactors, for example, to carry out hydrogenation, oxidation, or chlorination of organic liquids. In most studies of the performance of bubble columns, water or aqueous solutions have been employed as the liquid phase (Shah et al., 1982). There is much less information on the nonadjustable design parameters, specifically, the gas holdup ϵ_G and the volumetric mass transfer coefficient k_La, as far as organic liquids are concerned. Equations 1–10 in Table 1 present the pertinent empirical correlations of ϵ_G and k_La.

Owing to the greater difficulty of k_La determination, there are only two correlations, Eqs. 9 and 10, suggested by Akita and Yoshida (1973) and Hikita et al. (1981), respectively, with rather narrow experimental data bases. As in the gas holdup correlations, Eqs. 2 and 8, suggested by the same authors, Hikita et al. considered the influence of the gas properties, whereas Akita and Yoshida observed no significant effect when using different gases. Smaller gas holdups were reported for hydrogen as compared to nitrogen sparging by Bhaga et al. (1971), whereas no effect was observed by Kölbel et al. (1961) and Deckwer et al. (1980) when varying gas pressure by factors of 17 and 3, respectively.

With respect to the liquid properties, the applicability of the correlations appears questionable judged by recent experimental results. Vermeer and Krishna (1981) and Godbole et al. (1984) measured k_La in isoparaffin mixtures of about the same density, viscosity, surface tension, and (calculated) gas diffusivity, but the results do not match and are not well represented by suggested correlations (Godbole et al., 1984). The difference might refer to the different experimental techniques used in these studies, specifically, the analysis of gas phase residence time distribution (Vermeer and Krishna) and the dynamic oxygen absorption method (Godbole et al.). On the other hand, the set of properties considered might be incomplete. With respect to the gas holdup in liquid mixtures, this conclusion has been drawn by many investigators (Bach and Pilhofer, 1978; Bhaga et al., 1971; Gestrich and Rähse, 1975; Kelkar et al., 1983; Quicker and Deckwer, 1981).

It is the purpose of this paper to assess the influence of the liquid and gas properties on the gas holdup and the volumetric mass transfer coefficient. A comprehensive set of organic liquids is studied in order to check on the applicability of the correlations (Eqs. 1–10) listed in Table 1.

Experimental Methods

The experiments were carried out in a jacketed glass bubble column of 0.095 m dia. at a clear liquid height of 0.85 m. A single tube of 3 mm ID served as the gas distributor. Air, nitrogen, carbon dioxide, helium, or hydrogen was employed as the gas phase. The superficial gas velocity was controlled with a mass flow meter and ranged from 0.008 to 0.1 m/s (based on the mean hydrostatic head and the assumption of saturation by liquid vapor). Before entering the column, the gas passed through a drying tower and a saturator filled with the same liquid and thermostated to the same temperature (293 ± 1 K) as the bubble column.

As the liquid phase, 17 pure organic liquids, 5 inherently mixed liquids, and 17 adjusted mixtures were employed. Gases other than air were used only with carbon tetrachloride, xylene,

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Table 1. Correlations suggested for the gas holdup and the volumetric mass transfer coefficient in organic liquids

Correlation	Eq. No.	Systems	Reference
$\epsilon_G = [2 + (0.35/u_G)(\rho_L\sigma/72)^{1/3}]^{-1}$	(1)	Air/water, aq. solns., kerosene, light oil	Hughmark (1967)
$\dfrac{\epsilon_G}{(1-\epsilon_G)^4} = 0.2\left(\dfrac{gD_c^2\rho_L}{\mu_L}\right)^{1/8}\left(\dfrac{gD_c^3\rho_L^2}{\mu_L^2}\right)^{1/12}\left(\dfrac{u_G}{\sqrt{gD_c}}\right)$	(2)	(Air, He, CO_2)/water, aq. solns., methanol	Akita & Yoshida (1973)
$\epsilon_G = 0.505\, u_G^{0.47}(0.072/\sigma)^{2/3}(0.001/\mu_L)^{0.05}$	(3)	Air/water, methanol solns.	Hikita & Kikukawa (1974)
$\epsilon_G = 0.89\left(\dfrac{L_o}{D_c}\right)^{0.035(-15.7+\log K)}\left(\dfrac{d_B}{D_c}\right)^{0.3}$ $\cdot\left(\dfrac{u_G^2}{d_Bg}\right)^{0.025(2.6+\log K)}K^{0.047} - 0.05$ with $d_B = 0.003$ m and $K = \rho_L\sigma^2/(g\mu_L^4)$	(4)	Air/15 hydrocarbon liquids	Gestrich & Rähse (1975)
$\epsilon_G = 0.728\,U - 0.485\,U^2 + 0.0975\,U^3$ with $U = u_G\{\rho_L^2/[\sigma(\rho_L-\rho_G)g]\}^{1/4}$	(5)	Air/water, aq. solns. kerosene	Kumar et al. (1976)
$\dfrac{\epsilon_G}{(1-\epsilon_G)} = 0.0115\left[\dfrac{u_G^3\,\rho_L}{\mu_L g(\rho_L-\rho_G)/\rho_L}\right]^{0.23}$	(6)	Air/alcohols, halogenated hydrocarbons	Bach & Pilhofer (1978)
$\dfrac{\epsilon_G}{(1-\epsilon_G)^4} = 0.14\,u_G\left[\dfrac{\rho_L^2}{\sigma(\rho_L-\rho_G)g}\right]^{1/4}$ $\cdot\left[\dfrac{\rho_L^2\sigma^3}{\mu_L^4(\rho_L-\rho_G)g}\right]^{1/24}\left(\dfrac{\rho_L}{\rho_G}\right)^{1/36}\left(\dfrac{\rho_L}{\rho_L-\rho_G}\right)^{1/3}$	(7)	Semitheoretical	Mersmann (1978)
$\epsilon_G = 0.672\left(\dfrac{u_G\,\mu_L}{\sigma}\right)^{0.578}\left(\dfrac{\mu_L^4\,g}{\rho_L\,\sigma^3}\right)^{-0.131}$ $\cdot\left(\dfrac{\rho_G}{\rho_L}\right)^{0.062}\left(\dfrac{u_G}{u_L}\right)^{0.107}$	(8)	(Air, H_2, $H_2 + N_2$, CO_2, CH_4, C_3H_8)/water, aq. solns., methanol, 1-butanol, aniline	Hikita et al. (1980)
$\left(\dfrac{k_LaD_c^2}{D_L}\right) = 0.6\left(\dfrac{\mu_L}{\rho_LD_L}\right)^{0.5}\left(\dfrac{gD_c^2\rho_L}{\sigma}\right)^{0.62}$ $\cdot\left(\dfrac{gD_c^3\rho_L^2}{\mu_L^2}\right)^{0.31}\epsilon_G^{1.1}$	(9)	(Air, O_2, CO_2, He)/water, glycol and methanol (pure and aq. solns.)	Akita & Yoshida (1973)
$\left(\dfrac{k_La\,u_G}{g}\right) = 14.9\left(\dfrac{u_G\mu_L}{\sigma}\right)^{1.76}\left(\dfrac{\mu_L^4\,g}{\rho_L\,\sigma^3}\right)^{-0.248}$ $\cdot\left(\dfrac{\mu_G}{\mu_L}\right)^{0.243}\left(\dfrac{\mu_L}{\rho_LD_L}\right)^{-0.604}$	(10)	(Air, O_2, CH_4, H_2)/water, aq. solns. of sucrose and methanol, 1-butanol	Hikita et al. (1981)

and tetralin. Overall, 418 gas holdup values and 400 volumetric mass transfer coefficients were measured in 50 different gas/liquid systems. The gas and liquid properties varied in the following ranges (the individual values are tabulated in supplementary material).

$$0.29 \le 10^9 D_L \le 5.85 \text{ m}^2/\text{s}$$

$$714 \le \rho_L \le 1{,}593 \text{ kg/m}^3$$

$$0.33 \le 10^3 \mu_L \le 20 \text{ Pa s}$$

$$20.4 \le 10^3 \sigma \le 72.7 \text{ kg/s}^2$$

$$0.09 \le \rho_G \le 2.46 \text{ kg/m}^3$$

$$8.8 \le 10^6 \mu_G \le 19.4 \text{ Pa s}$$

$$0.008 \le u_G \le 0.1 \text{ m/s}$$

The liquid densities were measured in a pyknometer; the viscosities were measured in capillary viscometers; and the surface tensions were measured by the ring removal method. The results agree well with the available literature data. The gas properties were calculated as recommended by Reid et al. (1977), accounting for vapor pressure of the liquid. With respect to the oxygen diffusivities in the liquids, the predictions of the pertinent correlations (Reid et al.) were found to differ by factors up to 2. Therefore, measurements were carried out in a polarographic diffusion cell, the results being reported in a separate paper (Lühring and Schumpe, 1986). The following empirical correlation was suggested for the oxygen diffusivity at 293 K:

$$\underset{\text{m}^2/\text{s}}{D_L} = 5.0 \cdot 10^{-11}\ \underset{\text{Pa s}}{\mu_L^{-0.57}} \tag{11}$$

In cases where no experimental data are available, the predictions of Eq. 11 are considered.

The gas holdup was determined from the change in dispersion height due to the gas flow. The volumetric mass transfer coefficients were investigated by dynamic oxygen absorption or desorption methods. The oxygen fugacity in the liquids was measured with a polarographic oxygen electrode (WTW-EO 90) inserted horizontally at half the dispersion height. The electrode response time was 3 s in water and less in most organic liquids. In some liquids the electrode could be operated only for less than an hour, but even then there was sufficient time to take all readings. For absorption runs, oxygen was desorbed by sparging nitrogen. After disengagement of all nitrogen bubbles, a preadjusted air flow was fed by switching two magnet valves, and the increase in oxygen fugacity was recorded. For desorption runs, oxygen-free gas (N_2, CO_2, He, H_2) was sparged into air-saturated liquid. In the case of CO_2, no reliable k_La data could be obtained since the high solubility caused the initial CO_2 absorption to decrease the interfacial area available for oxygen desorption.

The electrode reading c_E in arbitrary units can be used and the response time need not be considered if the initial part (up to 50%) of the concentration change is neglected. Then, k_La values evaluated according to the relation

$$\ln (c_{E,\infty} - c_E) = -\frac{k_La}{\epsilon_L} t + \text{const.} \tag{12}$$

in the case of absorption runs, or

$$\ln c_E = -\frac{k_La}{\epsilon_L} t + \text{const.} \tag{13}$$

in the case of desorption runs agree well with the results of more sophisticated approaches that consider the time constant, or with the results of independent measurements using a steady-state method (Schumpe, 1985).

Results and Discussion

Gas holdup

Some of the gas holdups observed in organic liquids are plotted as a function of the superficial gas velocity in Figure 1. Except for ethylene glycol and its solutions, the gas holdups in the organic liquids are generally higher than those in water. The data fall in a rather narrow range except for ligroin. The behavior of the paraffin mixtures corresponds to the trends observed in the adjusted mixtures of benzene and cyclohexane and toluene and ethanol, Figure 2. In both systems there is a gas holdup maximum at intermediate mole fractions, the effect being much more pronounced in the case of the latter mixtures of a nonpolar and a polar substance. Bhaga et al. (1971) also studied the holdup in toluene/ethanol mixtures and observed the maximum gas holdup to be more than twice that in the pure components. This stronger effect is probably related to the porous plate sparger used by Bhaga et al., as a result of which more small bubbles are formed. The stabilization and, consequently, accumulation of these tiny bubbles might be responsible for the high gas holdups encountered in the mixed liquids. When applying a perforated plate with 19 × 1 mm holes and a single tube of 0.9 mm ID as the gas sparger, the gas holdups in ligroin A did not differ by more than 20% from the curve in Figure 2.

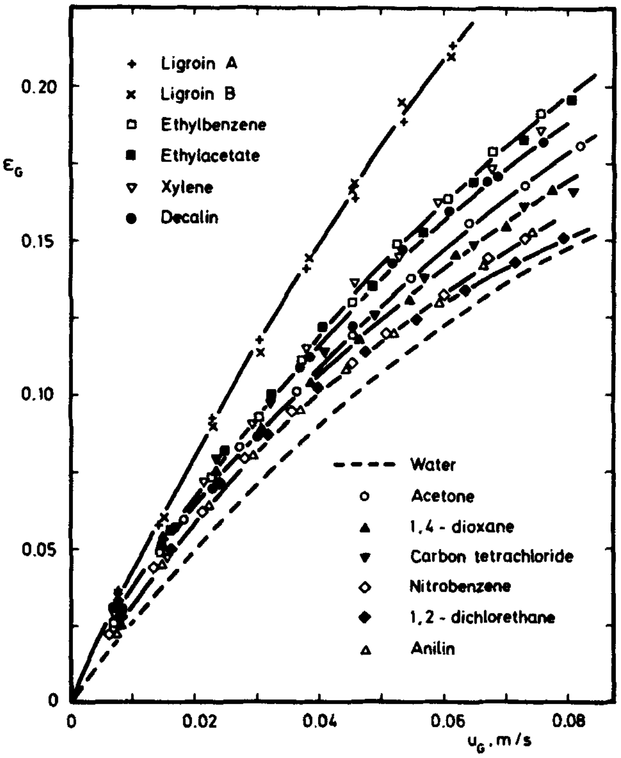

Figure 1. Gas holdups in various organic liquids.
Ligroin A b.p. = 90–110°C
Ligroin B b.p. = 100–140°C

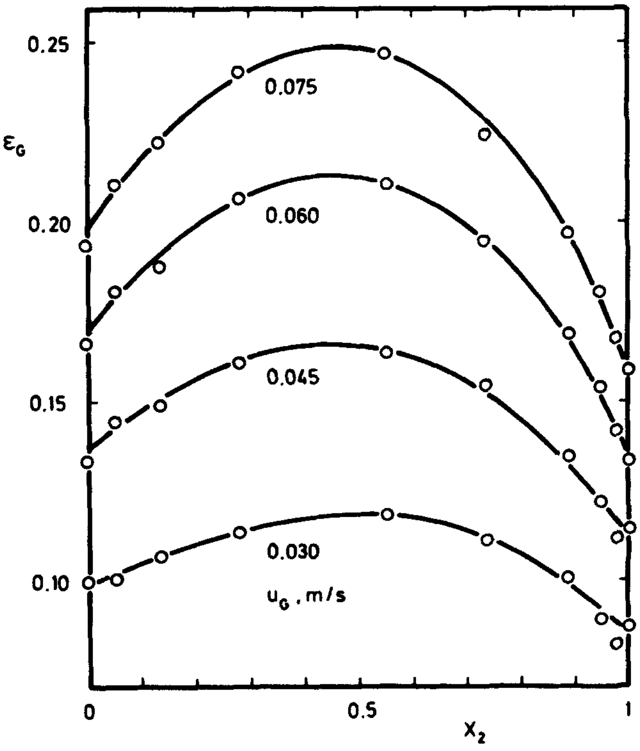

Figure 2. Gas holdups in toluene (1)/ethanol (2) mixtures.

The effect of the gas properties is illustrated in Figure 3 for xylene. The gas holdup monotonically increases with increasing density of the gas. The correlation is not consistent if the gas viscosity is considered, because the highest ϵ_G values are observed in the case of CO_2, whereas the highest gas viscosity is encountered in the case of helium. A very similar trend is observed in tetralin, whereas in carbon tetrachloride the differences are rather small. The behavior is in accord with the dominating influence of the high carbon tetrachloride vapor pressure on the gas density. The gas-specific effects are probably related to the bubble formation at the sparger rather than the hydrodynamics in the bulk of the dispersion. This might explain why the effect was observed only at moderate dispersion heights $L < 1$ m (Bhaga et al., 1971; Hikita et al., 1980) as used in this study, but not by Akita and Yoshida (1973) at $2 \text{ m} < L < 3$ m.

It is obvious that the high gas holdups encountered in benzene/cyclohexane and toluene/ethanol mixtures and in ligroin A and B do not correlate with the liquid properties. Therefore, these data are not considered when comparing the observed holdups to the correlations listed in Table 1. Further, the gas holdups at superficial gas velocities smaller than 0.01 m/s are left out because of the formation of unusually large bubbles and occasional weeping of the liquid. The results are summarized in Table 2. Among the applicable correlations, those of Akita and Yoshida, Eq. 2, and Hikita et al., Eq. 8, give the best fit. The deviations are rather systematic in case of some other correlations. This is illustrated by the factors by which the relations would have to be modified for an optimal fit. These factors are near 1 in the case of Eqs. 2 and 8. With mean errors around 11%, both relations can be recommended for design purposes. The fit of Eq. 2 could be improved by considering the density ratio of the phases. However, no new relation is proposed since the accuracy of the holdups measured in this study is certainly limited because of the moderate dispersion height employed.

Mass transfer

The volumetric mass transfer coefficients determined in alcohols, glycol solutions, and various organic liquids are plotted against the superficial gas velocity in Figures 4 and 5. The mass transfer coefficient is much more sensitive to the liquid properties than the gas holdup. At the same u_G, k_La varies by up to a factor of 10 as compared to a factor of 2 in the case of ϵ_G. The variation is mainly due to the viscosity effect on the diffusion coefficient, which causes k_La in glycol solutions and aniline to be particularly low. The most surprising result is that the mass transfer coefficients in ligroin A and B are close to those in pure liquids of similar properties in spite of the exceptionally high gas holdups. It is concluded that part of the holdup does not contribute to gas/liquid mass transfer. Specifically, the tiny bubbles accumulating in liquid mixtures are in equilibrium with the liquid phase.

Table 2. Comparison of Gas Holdups in Pure Liquids (269 Data Points, Excluding Ligroin) with Various Original and Modified Correlations

Correlation	Mean Error, % Orig. Eq.	Modif. Factor	Mean Error, % Modif. Eq.
Eq. 1, Hughmark (1967)	13.4	0.88	10.3
Eq. 2, Akita & Yoshida (1973)	11.2	1.10	9.7
Eq. 3, Hikita & Kikukawa (1974)	96.0	0.49	17.3
Eq. 4, Gestrich & Rähse (1975)*	—	—	—
Eq. 5, Kumar et al. (1976)	70.0	0.58	9.6
Eq. 6, Bach & Pilhofer (1978)	40.5	0.69	13.5
Eq. 7, Mersmann (1978)	18.3	1.30	10.1
Eq. 8, Hikita et al. (1980)	10.7	0.97	10.1

*Not applicable at $d_o = 0.003 \text{ m} > 0.2 \cdot d_B \approx 0.0006$ m

This conclusion is supported by the results obtained in mixtures of benzene and cyclohexane and of toluene and ethanol, Figure 6. The maximum with respect to k_La is much less pronounced, compared to Figure 2. Obviously, the tiny bubbles responsible for the high gas holdup hardly contribute to gas-

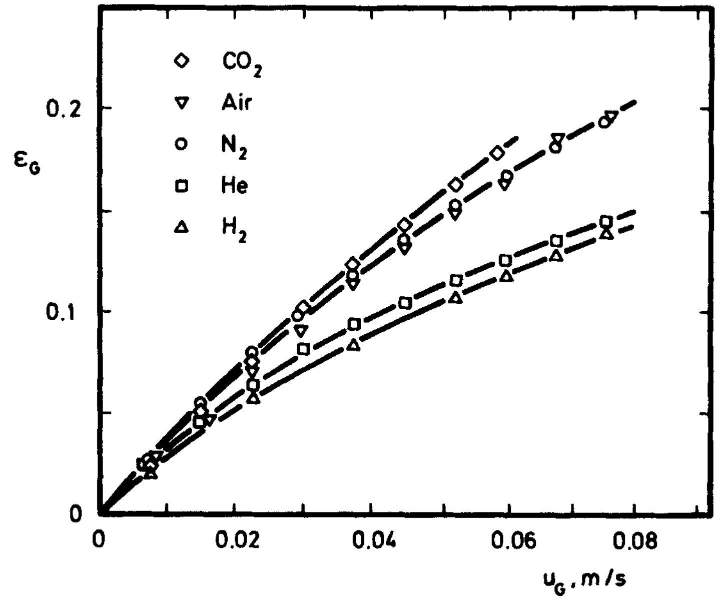

Figure 3. Holdups of various gases in xylene.

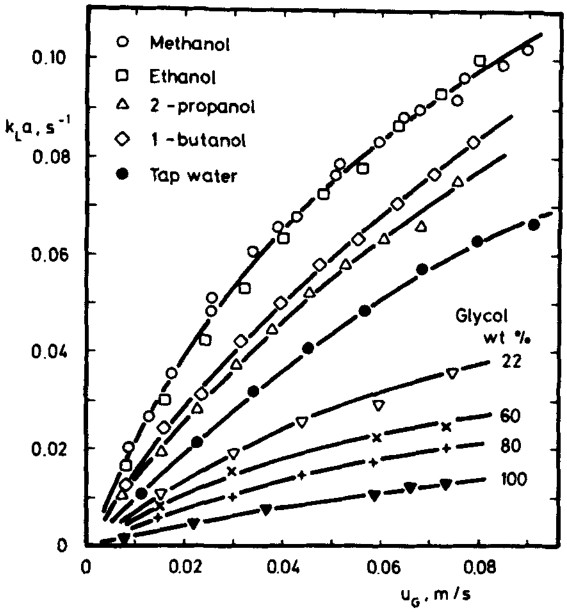

Figure 4. Volumetric mass transfer coefficients in alcohols and glycol solutions.

liquid mass transfer. Rather than their steady-state holdup, the rate of their formation will determine their contribution to k_La. This rate might be higher in the case of other liquid mixtures and more effective spargers such as porous plates.

The effect of the gas properties on k_La in xylene, Figure 7, is similar to that observed on ϵ_G, Figure 3. Similar results were obtained in tetralin, but no significant effects were observed when sparging different gases into carbon tetrachloride because its high vapor pressure determines the gas properties.

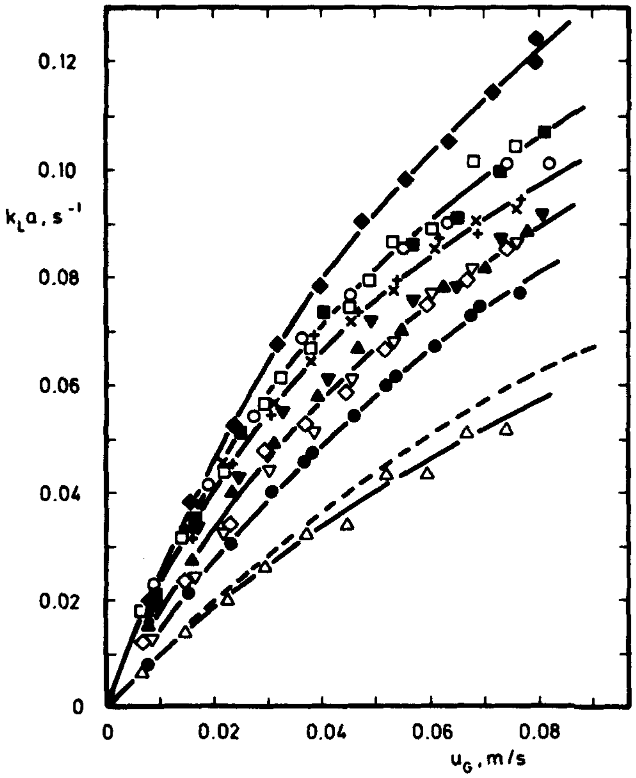

Figure 5. Volumetric mass transfer coefficients in various organic liquids.
Symbols as in Figure 1

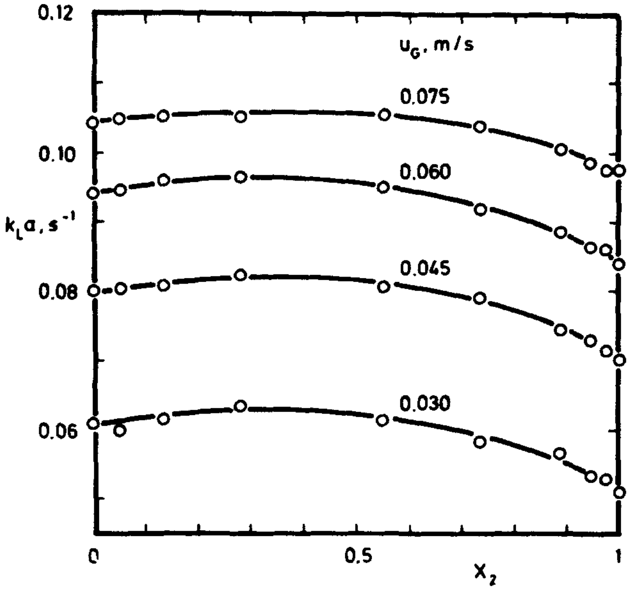

Figure 6. Volumetric mass transfer coefficients in toluene (1)/ethanol (2) mixtures.

For the comparison with the correlations suggested by Akita and Yoshida (1973) and Hikita et al. (1981), 360 data points at $u_G > 0.01$ m/s are considered, including those on mixed liquids. The results are listed in Table 3. Using the original form of the correlations, Eq. 9 by Akita and Yoshida gives a much better fit; if a modification factor is allowed for, Eq. 10 by Hikita et al. exhibits a slightly smaller error. The modified Akita-Yoshida correlation gives a better fit if the predicted rather than the experimental holdup is used. This also indicates that part of the gas holdup in mixed liquids does not contribute to mass transfer.

Even if modified by an optimized factor, the literature correlations describe the data with mean errors exceeding 20%. This is considered rather unsatisfactory as compared to a reproducibility of the data within 5%. Therefore, a new correlation is developed based on the present results. The modification of the Akita-Yoshida correlation suggested by Nakanoh and Yoshida (1980) is used since this functional form has already been successfully applied to correlate k_La in viscous liquids (Schumpe and Deckwer, 1987). The relation is modified by considering the density ratio of the phases. Further, the surface-to-volume mean bubble diameter d_B rather than the column diameter is used as the characteristic length, because even in highly viscous media where coalescence to large bubbles and gas slugs occurs, the column diameter has little influence on k_La (Schumpe and Deckwer). Specifically, the values of B_1–B_6 are optimized by Marquardt's technique in the following relation:

$$\left(\frac{k_La\,d_B^2}{D_L}\right) = B_1\left(\frac{\mu_L}{\rho_L D_L}\right)^{B_2}\left(\frac{g\rho_L d_B^2}{\sigma}\right)^{B_3} \cdot \left(\frac{g\rho_L^2 d_B^3}{\mu_L^2}\right)^{B_4}\left(\frac{u_G}{\sqrt{g d_B}}\right)^{B_5}\left(\frac{\rho_G}{\rho_L}\right)^{B_6} \quad (14)$$

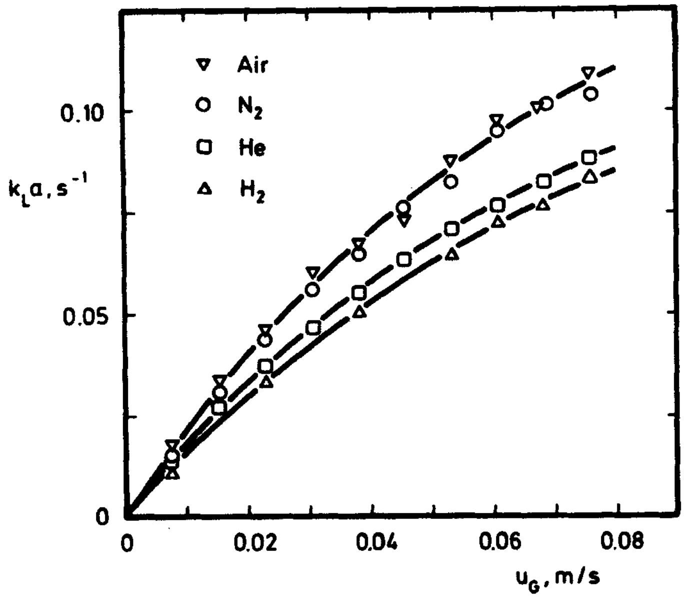

Figure 7. Influence of gas properties on k_La for oxygen transfer in xylene.
▽ absorption, ○□△ desorption

The bubble diameters have not been investigated in this study but by Quicker and Deckwer (1981) using the same bubble column. In xylene, decalin, and *n*-paraffins (C_{10}–C_{14}) Sauter mean diameters of about 3 mm were observed irrespective of the type of liquid and the temperature (333–443 K). As suggested by Gestrich and Rähse (1975), the constant value of

$$d_B = 0.003 \text{ m} \tag{15}$$

is introduced.

The result of the parameter optimization is given in Eq. 16.

$$Sh = 0.62\, Sc^{0.50}\, Bo^{0.33}\, Ga^{0.29}\, Fr^{0.68} \left(\frac{\rho_G}{\rho_L}\right)^{0.04} \tag{16}$$

The following dependencies are implied:

$$k_La \propto D_L^{0.50} \rho_L^{0.37} \mu_L^{-0.08} \sigma^{-0.33} \rho_G^{0.04} d_B^{-0.81} u_G^{0.68} \tag{17}$$

Table 3. Comparison of Volumetric Mass Transfer Coefficients (360 Data Points) with Suggested Correlations

Correlation	Mean Error, % Orig. Eq.	Modif. Factor	Mean Error, % Modif. Eq.
Eq. 9, Akita & Yoshida (1973) with exp. ϵ_G values	23.7	0.97	23.7
Eq. 9, Akita & Yoshida (1973) with ϵ_G predicted by Eq. 2	25.7	1.15	21.7
Eq. 10, Hikita et al. (1981)	37.2	0.71	20.5
Eq. 16, this work	13.3	—	—

The dimensionless numbers were varied in the following ranges:

$$1.6 \times 10^1 \leq Sh \leq 9.7 \times 10^2$$
$$3.2 \times 10^1 \leq Sc \leq 1.5 \times 10^5$$
$$1.2 \times 10^0 \leq Bo \leq 5.4 \times 10^0$$
$$8.3 \times 10^2 \leq Ga \leq 1.5 \times 10^6$$
$$4.3 \times 10^{-2} \leq Fr \leq 6.0 \times 10^{-1}$$
$$9.3 \times 10^{-5} \leq \rho_G/\rho_L \leq 2.0 \times 10^{-3}$$

As indicated in Table 3, Eq. 16 describes 360 measured k_La values with a mean error of only 13.3%. The parity plot, Figure 8, shows that maximum errors around 30% are observed. The k_La values measured by Godbole et al. (1984) in a mixture of isoparaffins in a column of 0.305 m dia. are also well described; only values at $u_G > 0.1$ m/s tend to be low as compared to Eq. 16. The same trend is observed in the case of high viscosity (ethylene glycol) and might result from large bubble diameters ($d_B > 0.003$ m) at high u_G and high μ_L. The dependence on the bubble diameter ($k_La \propto d_B^{-0.81}$) is a purely formal result but does not seem unreasonable considering that

$$a = \frac{6\epsilon_G}{d_B} \tag{18}$$

and k_L hardly depends on d_B if $d_B > 2.5$ mm (Calderbank and Moo-Young, 1961).

The result on the diffusion coefficient effect exactly corresponds to the penetration theory, as expected for bubble diameters exceeding 2.5 mm (Calderbank and Moo-Young). It should be noted that this result is based on the use of experimental diffusivities and the predictions calculated from Eq. 11. Also tested (as far as applicable) were Scheibel's modification of the Wilke-Chang equation recommended for organic liquids by Reid et al.

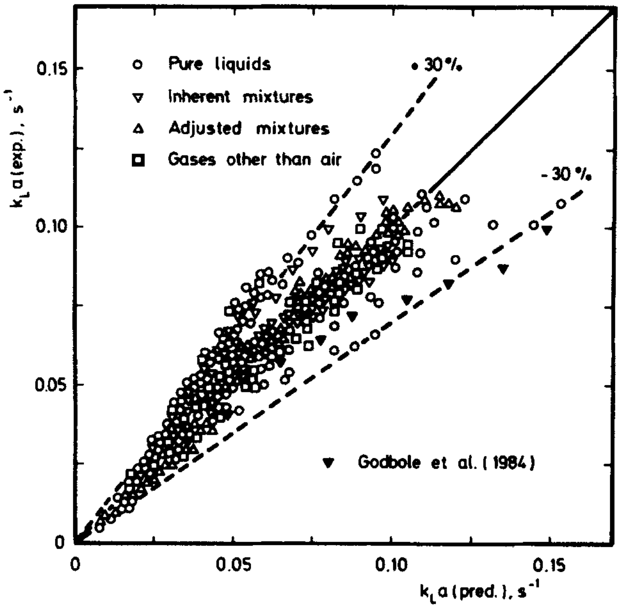

Figure 8. Parity plot for Eq. 16.

(1977) and the relations of Sovova (1976) with different viscosity effects for three groups of liquids. In both cases the optimized exponents of the Schmidt number are high and mean errors of 17.1 and 18.5%, respectively, are encountered as compared to 13.3% with the suggested approach.

Conclusions

Gas holdups and volumetric mass transfer coefficients were measured in various organic liquids in a bubble column. In some of the inherently mixed liquids and adjusted mixtures, the observed gas holdups are high as compared to pure liquids with similar density, viscosity, and surface tension. The rest of the data, however, are reasonably well described by the correlations suggested by Akita and Yoshida (1973) and Hikita et al. (1980).

Both the gas holdup and the volumetric mass transfer coefficient k_La are found to increase with the gas density. Surprisingly, the k_La values in the mixed liquids do not correlate with the high gas holdup but are close to those in pure liquids of similar properties. It is suggested that the tiny bubbles accumulating in the mixtures hardly contribute to mass transfer but are only circulated in the dispersion. The measured k_La data agree only approximately with previously suggested correlations. A new relation, Eq. 16, is developed that describes the volumetric mass transfer coefficients in all gas/liquid systems studied, with 13.3% mean error.

Acknowledgment

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Notation

a = specific interfacial area, referred to dispersion volume, m^{-1}
Bo = Bond number = $g\rho_L d_B^2/\sigma$
c_E = reading of oxygen electrode, arbitrary units
d_B = surface-to-volume mean bubble dia., m
D_C = column dia., m
D_L = diffusion coefficient, m$^2 \cdot$ s^{-1}
g = gravity acceleration, m $\cdot$ s^{-2}
Ga = Gallilei number = $g\rho_L^2 d_B^3/\mu_L^2$
Fr = Froude number = $u_G/\sqrt{g d_B}$
k_L = liquid side mass transfer coefficient, m $\cdot$ s^{-1}
k_La = volumetric mass transfer coefficient, referred to dispersion volume, s^{-1}
L = dispersion height, m
Sc = Schmidt number = $\mu_L/(\rho_L D_L)$
Sh = Sherwood number = $k_L a d_B^2/D_L$
t = time, s
u_G = mean superficial gas velocity, m $\cdot$ s^{-1}
x = mole fraction

Greek letters

ϵ = phase holdup
μ = viscosity, Pa $\cdot$ s
ρ = density, kg $\cdot$ m^{-3}
σ = surface tension, kg $\cdot$ s^{-2}

Indices

G = gas
L = liquid

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