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Gas Hold-Up in Stirred Tank Reactors in the Presence of Inorganic Electrolytes

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Gas hold-up, ϵ_G, in Stirred Tank Reactors (STRs) with air–water systems has been extensively studied in the literature over a wide range of system configurations and operating parameters (Greaves and Barigou, 1990; Smith, 1991; Rewatkar et al., 1993). On the other hand, only few studies are available on ϵ_G in air-aqueous inorganic electrolyte solutions in STR. The presence of inorganic electrolytes in aqueous solutions is common in different industrial processes taking place in STR such as aerobic fermentation, gas absorption, etc. The presence of inorganic electrolytes increases the gas–liquid interfacial area by reducing the degree of bubble coalescence (Lee and Meyrick, 1970; Prince and Blanch, 1990). Therefore, ϵ_G in air–electrolyte systems is much higher than ϵ_G in air–water system under the same operating conditions. Most of the studies that propose correlations to estimate ϵ_G in air–electrolyte systems in STR are based on small diameter tanks (T 0.40 m) (Lee and Meyrick, 1970; Machon et al., 1977; Hassan and Robinson, 1977; Yung et al., 1977). Only Greaves and Barigou (1990) have studied and correlated ϵ_G in an air–electrolyte system in a large STR of diameter 1 m.

Lee and Meyrick (1970) used the parameter $\psi = c(d\sigma/dc)^2$ to characterize the effect of the presence of an electrolyte on gas hold-up. They concluded that for a particular value of ψ, irrespective of type and concentration of the electrolyte, fractional gas hold-up in STR is approximately constant at a given gas flow rate and impeller speed. However, Lee and Meyrick (1970) could not provide a correlation from which ϵ_G can be estimated directly.

Machon et al. (1977) presented a correlation using dimensionless terms such as We, Fl_G and the parameter ψ. However, they also could not present a single correlation for their gas hold-up data of different impeller sizes. Machon et al. (1977) attempted to compare their correlation with the data of Lee and Meyrick (1970), but could not show unanimity. They concluded that the constant term and exponents in their correlation depends upon the geometrical configuration. Yung et al. (1979) also attempted to correlate ϵ_G in an air–water system using dimensionless terms. Unfortunately, they could not provide a unique correlation that fits their data for different impellers satisfactorily.

Greaves and Barigou (1990) measured ϵ_G in an air–electrolyte system at electrolyte concentration above transition concentration in an STR of diameter 1 m equipped with disc turbine. They correlated the gas hold-up

Gas hold-up (ϵ_G) in air–aqueous electrolyte solutions in stirred tank reactors (STR) is correlated using a relative gas dispersion parameter, N/N_{cd} and a surface tension factor (STF), $(c/z)(d\sigma/dc)^2$. For electrolyte concentration below transition concentration (c_t) a single correlation in the form of $\epsilon_G = f(N/N_{cd}, vvm, STF)$ shows good agreement with gas hold-up data over a wide range of system and operating conditions. Above c_t no effect of STF on gas hold-up is observed and the correlation obtained is of the form $\epsilon_G = f(N/N_{cd}, vvm)$. Data available in the literature on large STR show good fit with the proposed correlation.

On a corrélé la rétention de gaz (ϵ_G) dans un mélange air-solutions d'électrolytes aqueuses dans des réacteurs à réservoir agité (RRA) à l'aide d'un paramètre de dispersion de gaz, N/N_{cd}, et d'un facteur de tension de surface (FTS), $(c/z)(d\sigma/dc)^2$. Pour une concentration d'électrolytes en-dessous de la concentration de transition (ct), une corrélation simple sous la forme $\epsilon_G = f(N/N_{cd}, vvm, FTS)$ montre un bon accord avec les données de rétention de gaz pour une vaste gamme de systèmes et de fonctionnement. Au-dessus de ct, on observe aucun effet du STF sur la rétention de gaz et la corrélation obtenue est de la forme $\epsilon_G = f(N/N_{cd}, vvm)$. Les données disponibles dans la littérature scientifique sur des RRA de grande taille montrent un bon accord avec la corrélation proposée.

Keywords: STR, electrolyte, gas hold-up, relative dispersion (N/N$_{cd}$), STF.

based on clinging cavity regime and large cavity regime. On comparing their correlation with correlations of Hassan and Robinson (1977) and Yung et al. (1979), Greaves and Barigou (1990) could not obtain satisfactory agreement. Greaves and Barigou (1990) attributed this fact to increased surface aeration in smaller tanks (T 0.40 m) and the exclusion of dependence of gas hold-up on the particular flow regime on operating conditions and specific geometric configuration. Smith (1991) also indicated that gas

Table 1. Experimental details of the work carried out by different investigators on ε_G in air-aqueous electrolyte solution in STR.

Investigator	Lee and Meyrick (1970)	Machon et al. (1977)	Hassan and Robinson (1977)	Yung et al. (1979)	Greaves and Barigou (1990)
Column diameter (T), m	0.304	0.29	0.15	0.40	1
Liquid level (H)	$H = T$	$H = T$	$H = T$	$H = T$	$H = T$
Type of impeller, diameter (D/T) and location (C/T)	DT; $D/T = 1/3$ $C/T = 1/3$	DT; $D/T = 0.26; 0.34$ $C/T = 0.36$	DT; $D/T = 1/3$ $C/T = 1/3$	4-paddle, DT; $D/T = 0.225$ to 0.45 $C/T = 0.225$ to 0.45	DT; $D/T = 0.25$ to 0.5 $C/T = 0.25$
Sparger design and location	Orifice sparger in the center of base	Tube sparger just below impeller	Orifice sparger at the bottom of vessel	Orifice sparger just below the impeller	Pipe sparger below the impeller
Vessel bottom	Flat	Flat	Flat	Flat and hemispherical	Flat
Range of impeller speed, rev/s	5 to 10	5 to 10	5 to 35	3.33 to 23.3	0.67 to 8.33
Range of gas flow rate, m^3/s	3.65×10^{-3} to 9.14×10^{-3}	5×10^{-3} to 25×10^{-3}	0.063×10^{-3} to 1.235×10^{-3}	1.22×10^{-4} to 27.2×10^{-4}	1.64×10^{-3} to 8.33×10^{-3}
Method of measurement of gas hold-up	Level sensing instrument made up of perforated vertical tube	Conductivity meter probe	Cathetometer directed at impeller shaft region	Using 30° inclined manometer connected to pressure tab	Conductivity probe at five positions
Electrolytes used and their concentration (M)	NaCl (0.05 to 0.50 M) Na$_2$SO$_4$ (0.05 to 0.25 M)	Na$_2$SO$_4$ (0.5 and 1 M) NaSCN (1 to 5 M) MgCl$_2$ (0.5 to 2.5 M) K$_2$CO$_3$ (0.04 to 0.79 M)	Na$_2$SO$_4$ (0.4 M)	NaCl (0.2 M and 0.4 M) Na$_2$SO$_4$ (0.03 M and 0.312 M)	NaCl (0.15 M)
Correlation proposed	An iterative method is proposed	For $D/T = 0.26$, $\varepsilon_G = 1.3 \times 10^{-4} (We)(Fl_G)^{0.36} \cdot (Y)^{0.56}$ For $D/T = 0.34$, $\varepsilon_G = 9 \times 10^{-4}(We)^{0.73} (Fl_G)^{0.36} \cdot (Y)^{0.34}$ $Y = f(\ )$	$\varepsilon_G = 0.209 (Q_G N^2/\ )^{0.44}$	$\varepsilon_G (Fl_G)^{0.5}(We)^{0.65}(D/T)^{1.4}$	$\varepsilon_G = 4.2 (N)^{0.79}(Q_G)^{0.52} (D/T)^{1.92}$

hold-up correlations for larger tanks (T 0.44 m) do not show agreement with gas hold-up data for smaller tanks in air–water systems.

Experimental conditions of the studies carried out by different investigators who proposed correlations for estimating gas hold-up in non-coalescing systems in STR are given in Table 1.

In our previous work (Yawalkar et al., 2002) on ε_G in an air–water system in an STR, it was shown that gas hold-up data of different workers for larger tanks (Greaves and Barigou, 1990; Smith, 1991; Rewatkar et al., 1993; Yawalkar et al., 2002) can be reliably correlated by a single correlation based on the relative gas dispersion term, N/N_{cd}, over a wide range of system configurations ($T = 0.57$ m to 2.7 m, type of impellers: DT and PTD (45° pitched angle), $D/T = C/T = 0.25$ to 0.50, pipe sparger, conical sparger, ring sparger) and operating parameters (0.5 N/N_{cd} 1.5; $Q_G = 1 \times 10^{-3}$ to 1.50×10^{-1} m^3/s). N_{cd} is the minimum impeller speed for complete dispersion of the gas in the liquid phase in an STR. Greaves and Barigou (1990) and Smith (1991) presented correlations to estimate ε_G in an air–water system in an STR in larger tanks ($T = 0.61$ m to 2.7 m).

Smith (1991) concluded that above fractional gas hold-up of 0.08, ε_G values predicted by correlation of Greaves and Barigou (1990) are almost two times higher than those estimated from correlation of Smith (1991) for given system configuration and operating parameters. However, in our previous study (Yawalkar et al., 2002) it was noted that when gas hold-up data of Greaves and Barigou (1990) and Smith (1991) are correlated using the gas dispersion parameter, N/N_{cd}, they show good agreement.

In the previous work (Yawalkar et al., 2002) the importance of the relative dispersion parameter N/N_{cd} was discussed. It was concluded that N/N_{cd} represents the relative amount of gas retained in the liquid at the given impeller speed N with respect to that at impeller speed N_{cd}. Thus, $\varepsilon_G/\varepsilon_{Gcd} = f(N/N_{cd})$. For any economical gas–liquid mixing operation in an STR N_{cd} must be known, because at N_{cd} complete dispersion of the gas in the liquid phase is achieved (Nienow et al., 1977; Chapman et al., 1983; Rewatkar and Joshi, 1993). At an impeller speed below N_{cd} there is less or no gas in the region below the impeller. Therefore, the lower part of the tank is wasted, resulting in poor performance of the STR. N_{cd} can be determined by simple

methods such as by visual observation, from power input curve (N_{PG}/N_{Po} versus Fl_G curve) and mixing time studies (Rewatkar and Joshi, 1993). Also, reliable correlations for N_{cd} are available for different impellers in the literature (Nienow et al.,1977; Chapman et al., 1983; Rewatkar and Joshi, 1993).

In the present work an attempt has been made to provide a reliable correlation for ε_G in STRs with air–electrolyte systems using the relative gas dispersion parameter, N/N_{cd}. For this purpose ε_G data in an air–electrolyte system in an STR of diameter 0.57 m equipped with either a six-bladed standard disc turbine (DT) or six-bladed pitched turbine down flow [45° pitch angle (PTD)] were generated. Two correlations based on relative dispersion parameter (N/N_{cd}) for the gas hold-up data are obtained, one for electrolyte concentration below the transition concentration (c_t), and another for electrolyte concentration above the transition concentration. The transition concentration is the electrolyte concentration above which the gas bubble size in the air–electrolyte system remains constant (Prince and Blanch, 1990). The data of Greaves and Barigou (1990) for larger tanks show good agreement with the data of the present work when compared on the basis of the relative gas dispersion parameter, N/N_{cd}.

Surface Tension Factor (STF)

Salts inhibit bubble coalescence by retarding the thinning of the intervening liquid film between bubble pairs (Prince and Blanch, 1990). The surface area of this liquid film increases as film thinning proceeds. Therefore, surface excess of salt in the film increases as compared to that on the remainder of the bubble surface. The higher salt concentration produces an increase in the surface tension of the film. This results in a force opposite to the direction of flow at the gas–liquid boundary and an increase in thinning time of the liquid film during coalescence (Marrucci, 1969; Prince and Blanch, 1990). Thus, the presence of electrolyte hinders bubble coalescence and therefore reduces bubble size in a gas–electrolyte system.

As the concentration of electrolyte in the solution is increased, surface tension of the liquid film between adjacent bubbles further increases. Thus, the process of bubble coalescence further slows down, giving a still smaller bubble size. At a sufficiently high salt concentration, the force developed due to increased surface tension of the film immobilizes the gas–liquid interface. At and above such concentration, the bubble size remains stable and any further addition of electrolyte no longer has a pronounced influence. This concentration is termed transition electrolyte concentration (c_t) (Marrucci, 1969; Prince and Blanch, 1990). Prince and Blanch (1990) modified the expression for c_t given by Marrucci (1969). They gave:

$$c_t = 1.18z \left(\frac{B}{r_b}\right)^{1/2} R_g t \left(\frac{d\sigma}{dc}\right)^{-2}$$ (1)

This expression is based on the assumption that a retarded van der Waals attraction governs the interaction between molecules of liquid film between adjacent bubbles. Prince and Blanch (1990) have observed that c_t predicted from Equation (1) shows satisfactory agreement with experimental data on c_t.

As the concentration of solute is lower at the surface and higher at the center of the liquid film between coalescing bubbles, surface tension varies along the film thickness. This variation, given by Marrucci (1969) and Prince and Blanch (1990), is:

$$= -\frac{1}{zh} \frac{2c}{R_g t} \left(\frac{d\sigma}{dc}\right)^2$$ (2)

From the above discussion it can be concluded that the term σ characterizes the effect of type and concentration of electrolyte on bubble size in a gas–aqueous electrolyte system. In our previous work (Yawalkar et al., 2002), it was shown that for an air–water system ε_G can be reliably correlated over a wide range of system and operating conditions using the terms N/N_{cd} and vvm (volume of gas sparged per unit volume of liquid in a reactor per minute). Therefore in air–electrolyte systems ε_G can be assumed to be a function of N/N_{cd}, vvm and σ. At a given temperature σ depends upon concentration of solute in solution (c), $d\sigma/dc$, number of ions dissociated from one molecule of solute (z), and the thickness of liquid film between two coalescing bubbles (h). The film thickness h is a function of turbulence intensity prevailing in the tank (Lee and Meyrick, 1970) which in turn depends upon system configuration and operating parameters. Therefore, the term $1/h$ in Equation (2) can be considered to be a function of N/N_{cd} and vvm, while the remaining variable terms in Equation (2) can be grouped together as $(c/z) (d\sigma/dc)^2$ as a surface tension factor (STF). Therefore, gas hold-up in air–electrolyte systems in STR can be expressed as, $\varepsilon_G = f(N/N_{cd}, vvm, STF)$.

Experimental

Fractional gas hold-up was measured in a fully baffled (four baffles, each with width = 0.1T) acrylic tank of diameter 0.57 m for a gas–aqueous electrolyte solution system. Tap water was used for this purpose. Air was used as the gas phase. The different electrolytes used were NaCl, Na_2SO_4, KNO_3, KCl, KOH and $MgSO_4$. Gas hold-up data in aqueous solutions were obtained for different electrolyte concentrations below and above transition concentration (c_t). Two types of impellers were used: standard six-bladed disc turbines (DT) and six-bladed pitched down flow turbines with pitch angle of the blades of 45° (PTD). Gas was sparged through a perforated pipe sparger just below the impeller. In all the experiments clearance of the impeller from the tank bottom was maintained the same as the impeller diameter ($D/T = C/T$). The tank was rested on a torque table to measure power input. The bearing friction of the torque table was less than 2% of minimum agitation power consumption and it was accounted for in the calculation. For a given gas flow rate (vvm), values of ε_G were measured at three different impeller speeds, $N/N_{cd} = 0.5$, 1 and 1.5, i.e. from incomplete gas dispersion to thorough gas dispersion condition. Detailed experimental details are given in Table 2.

Measurement of N_{cd}

As discussed by Rewatkar and Joshi (1993), minimum impeller speed for complete dispersion of the gas N_{cd} was measured from the power input curve (N_{PG}/N_{Po} versus Fl_G curve) in the present work on air–electrolyte systems. It was observed that, for a particular impeller at a given gas flow rate, power input curve and therefore N_{cd} values obtained in the present work are almost the same as those obtained for air–water systems in our previous work (Yawalkar et al., 2002). Lee and Meyrick (1970), Bruijn et al. (1974) and Yung et al. (1979) also observed no

difference in power input on addition of electrolytes in an air–water system in an STR. Lee and Meyrick (1970) remarked that the power drawn by the impeller depends to a large extent on the size of large gas bubbles caught in the wakes of the impeller blades. Any change in these wakes and the manner in which the smaller bubbles break off from the wakes that might be caused by the solute therefore have insignificant effect on the drag upon the blades and hence the power consumed. N_{cd} values obtained in the present work agreed within ±10% with correlations of Nienow et al. (1977) and Rewatkar and Joshi

(1993) for DTs and PTDs, respectively. This observation is in agreement with our previous work (Yawalkar et al., 2002). Correlations of Nienow et al. (1977) and Rewatkar and Joshi (1993) for N_{cd} are based on wide range of system and operating conditions (Table 3). These correlations are:

$$N_{cd} = \frac{4(Q_G)^{0.5}(T)^{0.25}}{(D)^2} \tag{3}$$

for DT, and

$$N_{cd} = 2.143 \, (T)^{1.06}(D)^{-1.88}(V_G)^{0.35} \tag{4}$$

for PTD.

Measurement of Fractional Gas Hold-up (ϵ_G)
Fractional gas hold-up was measured by noting the dispersion heights in the presence and absence of gas sparging. ϵ_G is given by:

$$\epsilon_G = \frac{H_D - H}{H_D} \tag{5}$$

where H is the height of clear liquid above the tank bottom and H_D is the height of dispersion above the tank bottom.

The liquid surface fluctuates in the case of mechanically agitated gas–liquid contactors. Therefore, the height of dispersion was measured at two locations diametrically opposite to each other and midway between the two adjacent baffles at the periphery of the vessel. When the ϵ_G value is less than 3%, the reproducibility of measurement is within 10%. At higher values of holdup the reproducibility improves to within 5%. As experimentally determined, N_{cd} values agreed well (±10%) with values obtained from the correlations available in the literature (Equation 3 and Equation 4), analysis of the gas hold-up data

Table 2. Experimental details of the present work.

System used	Air–aqueous electrolyte solution
Tank diameter (T), m	0.57
Type of the impeller	DT, PTD (45° pitched angle)
Impeller diameter (D) and location (C), m	$D = C = 0.19; 0.25$
Sparger design and location, m	Perforated pipe sparger just below the impeller.
Vessel bottom	Flat
Liquid level (H)	$H = T$
Range of gas flow rate, m³/s	1×10^{-3} to 4×10^{-3}
Electrolytes used and their concentrations	NaCl (0.1 M, 0.25 M and 0.45 M) Na$_2$SO$_4$ (0.05 M, 0.067 M, 0.1 M, 0.15 M and 0.27 M) KNO$_3$ (0.15 M and 0.30 M) KCl (0.1 M, 0.2 M and 0.46 M) MgSO$_4$ (0.0315 M and 0.071 M) KOH (0.05 M and 0.354 M)

Table 3. Experimental details of Nienow et al's. (1977) and Rewatkar and Joshi's (1993) work for correlation of N_{cd} for DT and PTD, repectively.

Investigator	Nienow et al. (1977)	Rewatkar and Joshi (1993)
System used	Air–Water	Air–Water
Type of the impeller	DT	PTD
Column diameter (T), m	0.29 to 1.83	0.57 to 1.5
Liquid level (H)	$H = T$	$H = T$
Impeller diameter (D/T) and location (C/T)	$D/T = 0.125$ to 0.175 $C/T = 0.25$ to 0.41	$D/T = 0.25$ to 0.5 $C/T = 1/3$
Sparger design and location	Pipe point sparger, ring sparger just below the impeller	Concentric ring, pipe, porous ring and conical spargers. Location varied from 390 mm below the impeller to 35 mm above the impeller.
Vessel bottom	Flat, dished	Flat
Range of impeller speed or Maximum power input	1.9 to 8.2 W/kg	0.4 to 10.5 rev/s
Range of gas flow rate, m³/s	6.60×10^{-5} to 12.09×10^{-2}	8.93×10^{-4} to 5.30×10^{-2}

generated in the present work for $T = 0.57$ m was carried out based on N_{cd} values given by either Equation (3) or Equation (4) for DT or PTD, respectively.

Results and Discussion

Table 4 gives transition electrolyte concentration estimated by Prince and Blanch (1990) from Equation (1). The values of STF defined in the present work are also given for different electrolytes. From Table 4 it is evident that at c_t the bubble size and values of STF are approximately the same irrespective of type and concentration of the electrolyte. This demonstrates the importance of STF in defining/correlating influence of electrolyte on bubble size and therefore the gas hold-up.

In our previous work on ε_G in an air–water system (Yawalkar et al., 2002) it was noted that at a specific vvm, ε_G is approximately constant irrespective of tank size, type and size of the

Table 4. Transition electrolyte concentration (c_t) and corresponding STF values of some electrolytes of importance.

Electrolyte	$d\sigma/dc^* \times 10^4$, kg·m³/kmol·s⁴	Bubble radius (r_b), m × 10³	c_t, kmol/m³	STF × 10⁷, kg²·m³/kmol·s⁴
$MgSO_4$	32	0.18	0.042	2.15
$MgCl_2$	34	0.18	0.056	2.15
$CaCl_2$	35	0.18	0.053	2.16
Na_2SO_4	27	0.18	0.089	2.16
LiCl	16.20	0.18	0.165	2.16
NaCl	17	0.18	0.150	2.16
NaBr	13	0.18	0.257	2.17
KCl	14.40	0.18	0.209	2.16
K_2SO_4	25.20	0.205	0.096	2.03
KOH	17.80	0.205	0.128	2.01
$CuSO_4$	18.50	0.205	0.120	2.05
KI	8.40	0.205	0.580	2.04
KNO_3	10.40	0.205	0.376	2.03

* The values of $d\sigma/dc$ are taken from Prince and Blanch (1990). Also available in "Handbook of Chemistry and Physics" and "International Critical Tables".

Table 5. Gas hold-up data obtained in the present work for air–electrolyte solution at STF = 1.61 × 10⁻⁷ kg²·m³/kmol·s⁴.

vvm	Type and size of the impeller	N_{cd} (rev/s)	N/N_{cd}	ε_G for 0.0315 M $MgSO_4$ solution	ε_G for 0.30 M KNO_3 solution	ε_G predicted from Equation (6)	ε_G at zero electrolyte concentration
0.41	DT (0.19 m)	3.04	0.5	0.033	0.030	0.040	0.029
			1	0.065	0.078	0.074	0.045
			1.5	0.082	0.112	0.105	0.068
	PTD (0.19 m)	5.08	0.5	0.037	0.032	0.040	0.027
			1	0.073	0.080	0.074	0.050
			1.5	0.091	0.110	0.105	0.063
	DT (0.25 m)	1.76	0.5	0.039	0.033	0.040	0.031
			1	0.082	0.088	0.074	0.053
			1.5	0.115	0.121	0.105	0.071
	PTD (0.25 m)	3.03	0.5	0.040	0.052	0.040	0.035
			1	0.082	0.070	0.074	0.056
			1.5	0.122	0.112	0.105	0.070
1.65	DT (0.19m)	6.08	0.5	0.092	0.122	0.107	0.087
			1	0.17	0.213	0.194	0.135
			1.5	0.245	0.290	0.276	0.175
	PTD (0.19 m)	7.70	0.5	0.118	0.110	0.107	0.080
			1	0.198	0.225	0.194	0.131
			1.5	0.288	0.265	0.276	0.181
	DT (0.25 m)	3.51	0.5	0.10	0.095	0.107	0.088
			1	0.189	0.210	0.194	0.142
			1.5	0.25	0.320	0.276	0.190
	PTD (0.25 m)	4.59	0.5	0.127	0.120	0.107	0.088
			1	0.228	0.213	0.194	0.140
			1.5	0.315	0.30	0.276	0.188

Table 6. Gas hold-up data obtained in the present work for air-electrolyte solution at STF values above 2.07×10^{-7} $kg^2 \cdot m^3/kmol \cdot s^4$.

vvm	Type and size of the impeller	N_{cd} (rev/s)	N/N_{cd}	$_G$ for 0.25 M NaCl solution (STF = 3.61×10^{-7} $kg^2 \cdot m^3/kmol \cdot s^4$)	$_G$ for 0.1 M Na_2SO_4 solution (STF = 2.43×10^{-7} $kg^2 \cdot m^3/kmol \cdot s^4$)	$_G$ for 0.354 M KOH solution (STF = 5.60×10^{-7} $kg^2 \cdot m^3/kmol \cdot s^4$)	$_G$ predicted from Equation (7)	$_G$ at zero electrolyte concentration
0.41	DT (0.19 m)	3.04	0.5	0.042	0.054	0.039	0.049	0.029
			1	0.085	0.089	0.064	0.075	0.045
			1.5	0.112	0.118	0.085	0.100	0.068
	PTD (0.19 m)	5.08	0.5	0.037	0.040	0.040	0.049	0.027
			1	0.068	0.087	0.064	0.075	0.050
			105	0.090	0.105	0.092	0.100	0.063
	DT (0.25 m)	1.76	0.5	0.045	0.042	0.044	0.049	0.031
			1	0.077	0.097	0.070	0.075	0.053
			105	0.098	0.122	0.095	0.100	0.071
	PTD (0.25 m)	3.03	0.5	0.045	0.047	0.040	0.049	0.035
			1	0.076	0.070	0.070	0.075	0.056
			1.5	0.100	0.090	0.118	0.100	0.070
1.65	DT (0.19 m)	6.08	0.5	0.145	0.113	0.155	0.145	0.087
			1	0.252	0.250	0.245	0.242	0.135
			1.5	0.320	0.300	3.330	0.326	0.175
	PTD (0.19 m)	7.70	0.5	0.114	0.120	0.150	0.145	0.080
			1	0.209	0.206	0.220	0.242	0.131
			1.5	0.290	0.350	0.300	0.326	0.181
	DT (0.25 m)	3.51	0.5	0.150	0.122	0.165	0.145	0.088
			1	0.265	0.215	0.240	0.242	0.142
			1.5	0.346	0.291	0.350	0.326	0.190
	PTD (0.25 m)	4.59	0.5	0.132	0.160	0.150	0.145	0.088
			1	0.225	0.268	0.255	0.242	0.140
			1.5	0.296	0.345	0.354	0.326	0.188

Table 7. $_G$ data of different workers for an air–electrolyte system based on relative dispersion parameter, N/N_{cd}.

Researchers	Correlation obtained in the form of N/N_{cd}	R^2	Standard deviation	Number of data points analyzed
Lee and Meyrick (1970)[*]	$_G = 60.43 \, (N/N_{cd})^{0.863} \, (vvm)^{1.17} \cdot (STF)^{0.504}$	0.84	0.18	35
	$_G = 0.0260 \, (N/N_{cd})^{1.33} \, (vvm)^{1.30}$	0.92	0.13	36
Machon et al. (1977)[**]	$_G = 2.97 \, (N/N_{cd})^{1.25} \, (vvm)^{0.99}$	0.93	0.11	108
	For STF values corresponding to concentration below c_t: $_G \, (N/N_{cd})^{1.18} \, (vvm)^{0.95}$	-	-	36
Hassan and Robinson (1977)	$_G = 0.0428 \, (N/N_{cd})^{0.88} \, (vvm)^{0.88}$	1	-	12
Greaves and Barigou (1990)	$_G = 16.5 \times 10^{-2} \, (N/N_{cd})^{0.79} \, (vvm)^{0.91}$	0.97	0.10	27
	Including effect of D/T: $_G = 23.75 \times 10^{-2} \, (N/N_{cd})^{0.79} \, (vvm)^{0.91} (D/T)^{0.34}$ 0.97	1	-	27
Present work [*]	$_G = 2.97 \, (N/N_{cd})^{0.863} \, (vvm)^{0.70} \cdot (STF)^{0.197}$	0.95	0.12	420
	$_G = 15.81 \times 10^{-2} \, (N/N_{cd})^{0.73} (vvm)^{0.84}$	0.96	0.11	384

[*] Correlation incorporating the term STF is for electrolyte concentration below c_t while other correlation is for electrolyt concentration aboce c_t.
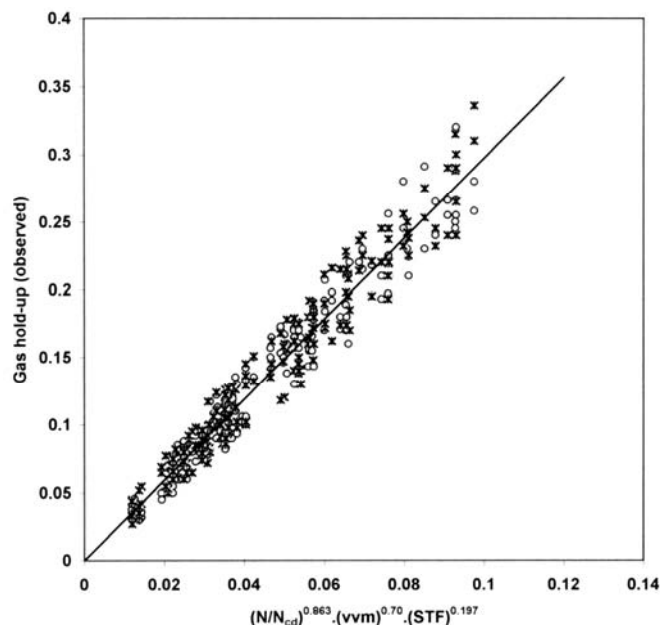[**] Data for different impeller sizes are analyzed together as $_G = f(N/N_{cd}, vvm)$.

Figure 1. Gas hold-up data fit by Equation (6) for electrolyte concentration below c_t. $\bigcirc$ – Gas hold-up data for DT; * – Gas hold-up data for PTD.

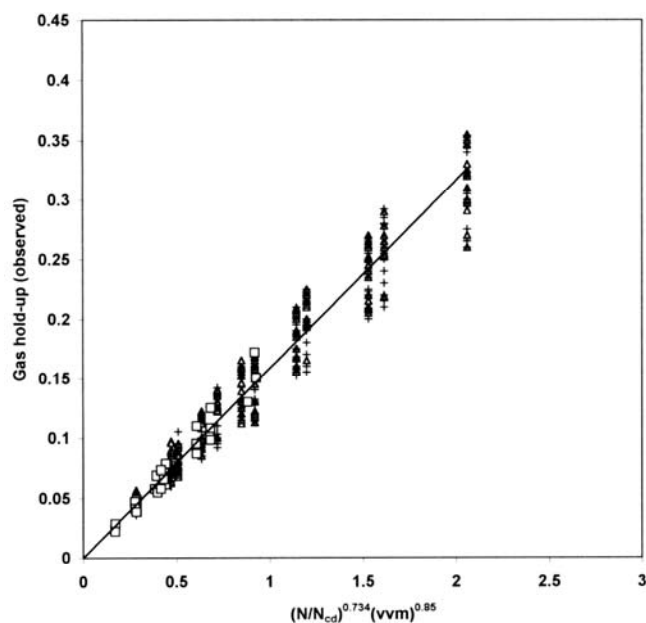**Figure 2.** Gas hold-up data fit by Equation (7) for electrolyte concentration above c_t. – Gas hold-up data for DT; + – Gas hold-up data for PTD; – Gas hold-up data of Greaves and Barigou (1990).

impeller, type and size of the sparger at a given N/N_{cd}. Analyzing the $_G$ data obtained in the present work it is also concluded that gas hold-up is approximately constant at given values of vvm, N/N_{cd} and STF for STF values between 7.9×10^{-8} to 2.07×10^{-7} kg$^2\cdot$m^3/kmol$\cdot$s^4 irrespective of type and size of the impeller, nature and concentration of the electrolyte. For STF values greater than 2.07×10^{-7} kg$^2\cdot$m^3/kmol$\cdot$s^4 gas hold-up is observed to be function of N/N_{cd} and vvm, irrespective of STF value of a salt solution under consideration. This result is in agreement with the conclusion derived from Table 4. Approximately, above this STF value, the bubble size in air–electrolyte system remains constant. Some of the gas hold-up data generated in the present work are given in Tables 5 and 6.

On regressing the data the correlations obtained are as follows. For, STF values between 7.9×10^{-8} to 2.07×10^{-7} kg$^2\cdot$m^3/kmol$\cdot$s^4:

$$_G = 2.97 \ (N/N_{cd})^{0.863} \ (vvm)^{0.70} \ (STF)^{0.197} \tag{6}$$

Equation (6) is based on more than 420 data points. The R^2 value of Equation (6) is 0.95 with standard deviation of 0.12. For STF values greater than 2.07×10^{-7} kg$^2\cdot$m^3/kmol$\cdot$s^4:

$$_G = 15.81 \times 10^{-2} \ (N/N_{cd})^{0.734} \ (vvm)^{0.85} \tag{7}$$

Equation (7) is based on a total of 384 data points with R^2 value of 0.96 and standard deviation of 0.11. Gas hold-up data along with correlating lines for both these expressions are given in Figures 1 and 2. Both the proposed correlations show good agreement with the $_G$ data of radial flow DTs and axial flow

PTDs. This buttresses the importance of the term N/N_{cd} (relative turbulence intensity or relative dispersion) in correlating gas hold-up in STR. The only data available in the literature on larger tanks are those of Greaves and Barigou (1990) for STR of diameter 1 m equipped with DTs. These data are for an air–0.15 M NaCl solution for which STF value is 216.75 kg$^2\cdot$m^3/kmol$\cdot$s^4 (at transition concentration). Figure 2 shows that Equation (7) proposed in the present work on $T = 0.57$ m fits well with the data of Greaves and Barigou (1990). Gas hold-up data for Greaves and Barigou's (1990) work used in Figure 2 were obtained strictly over the range of geometric configurations and operating parameters studied by them.

As discussed earlier most of the studies on $_G$ in an air–electrolyte system are based on smaller tanks with diameter 0.40 m. Table 7 shows that $_G$ data of different workers can be correlated satisfactorily in the form of $_G = f(N/N_{cd}, vvm, STF)$. However, the data for smaller tanks do not show good agreement with the data of the present work and those of Greaves and Barigou (1990) when defined on the basis of N/N_{cd}. Machon et al. (1977) presented two different correlations for two different sizes of impeller they studied. But when their data are correlated on the basis of the relative dispersion parameter N/N_{cd}, a single satisfactory correlation for both the data sets is obtained. Most of the data of Machon et al. (1977) are for STF values greater than 2.07×10^{-7} kg$^2\cdot$m^3/kmol$\cdot$s^4; therefore, the dependence of $_G$ on STF values for electrolyte concentration below c_t in the work of Machon et al. (1977) is not clear. Machon et al. (1977) raised doubts about the accuracy of the gas hold-up data of Lee and Meyrick (1970). Still, the data of Lee and Meyrick (1970) can be reasonably correlated on the basis of N/N_{cd}.

Table 8 shows some of the data of Greaves and Barigou (1990) in the form of $_G = f(N/N_{cd}, vvm)$ along with the estimated $_G$ values from the correlation proposed in the

Table 8. ε_G data of Greaves and Barigou (1990) in the form of ε_G, N/N_{cd} and vvm for tank diameter 1 m.					
vvm	D/T	N_{cd} (rev/s)	N/N_{cd}	ε_G observed	ε_G predicted Equation (7)
0.230	0.25	3.50	0.49	0.022	0.027
			1	0.038	0.045
			1.56	0.055	0.063
	0.33	2.01	0.50	0.024	0.027
			1	0.042	0.045
			1.49	0.058	0.060
	0.50	0.876	0.50	0.028	0.027
			1	0.048	0.045
			1.54	0.068	0.062
0.636	0.25	3.50	0.49	0.057	0.066
			1	0.098	0.107
			1.56	0.129	0.139
	0.33	2.01	0.50	0.065	0.068
			1	0.107	0.107
			1.49	0.150	0.146
	0.50	0.876	0.50	0.073	0.066
			1	0.124	0.108
			1.54	0.171	0.145

present work. A close look at Table 8 shows that, at a given N/N_{cd} and vvm, as D/T increases by 50%, ε_G approximately increases by 9% to 17%. In the present work no such clear effect of D/T on ε_G at a given N/N_{cd} and vvm is observed. However, in our previous work (Yawalkar et al., 2002), by studying a large amount of ε_G data for an air–water system in an STR with $T = 0.57$ m to 2.7 m and $D/T = 0.25$ to 0.5, it has been shown that the standard deviation of correlation of the type $\varepsilon_G = f(N/N_{cd}, vvm)$ can be further reduced by taking into account the effect of T and D/T by using $\varepsilon_G = f(N/N_{cd}, vvm, T, D/T)$. The correlation for data of Greaves and Barigou (1990) in the form of $\varepsilon_G = f(N/N_{cd}, vvm, D/T)$ is given in Table 7, which shows an excellent fit to the data points. Therefore, it can be agreed that the deviation of the data points around a correlations based on N/N_{cd} such as Equations (6) and (7) can be minimized further by generating and analyzing ε_G data in gas(air)–electrolyte system for STRs of tank sizes greater than 1 m with respect to D/T and T at given N/N_{cd} and vvm.

Conclusions

Correlations available in the literature for ε_G in an STR with an air–electrolyte system when applied to different system and operating conditions cannot predict gas hold-up satisfactorily. This discrepancy may be attributed to the exclusion of an existing flow regime in STR for a specific experiment, not taking into account changing boundary limits of the flow regimes with scale or neglecting the effect of any of the parameters on gas hold-up which may become important on scale-up.

By considering these facts in the present work, an attempt has been made to provide a correlation which will predict ε_G reliably over wide range of geometric configurations, electrolyte concentration, gas flow rate and impeller speed. A large amount of ε_G data for different electrolyte solutions of different concentrations are generated in an STR equipped with either radial flow DT or axial flow PTD. Two satisfactory correlations are obtained when ε_G data are analyzed on the basis of relative gas dispersion parameter, N/N_{cd}. One of the correlations incorporates variation of bubble size and, hence, ε_G with changing electrolyte concentration by taking into account surface tension gradient ( ) across a liquid film between two adjacent bubbles, for electrolyte concentration below transition concentration. For this purpose a surface tension factor (STF), $(c/z)(d\sigma/dc)^2$, is proposed. The other correlation is for electrolyte concentration above transition concentration (c_t), which does not show dependence of ε_G on

. The proposed correlation shows good agreement with the data available in the literature on a larger tank. The need to generate ε_G data in larger STRs ($T > 1$ m) with air–electrolyte systems for different D/T is emphasized. Thus, by incorporating the effect of D/T and T in a correlation based on N/N_{cd}, the deviation of data points around a correlating line can be further minimized, permitting more accurate estimation of gas hold-up.

Nomenclature

B	retarded van der Waals coefficient, (J·m)
C	clearance of the impeller from the bottom of STR, (m)
c	concentration, (kmol/m^3)
c_t	transition electrolyte concentration, (kmol/m^3)
D	impeller diameter, (m)
DT	six-bladed standard disc turbine
Fl_G	gassed flow number, (Q_G/ND^3)
f	activity coefficient
h	liquid film thickness between coalescencing bubbles, (m)
H	height of clear liquid in STR, (m)
H_D	height of gas–liquid dispersion in STR, (m)
N	impeller speed, (rev/s)
N_{cd}	minimum impeller speed for complete dispersion of the sparged gas, (rev/s)
N_{PG}	power number of the impeller in presence of gas, $P_G/\rho N^3 D^5$
N_{Po}	power number of the impeller in absence of gas, $P/\rho N^3 D^5$
PTD	six-bladed pitched turbine down flow, (45° pitch angle)
P_G	power input in presence of gas, (W)
P_O	power input in absence of gas, (W)
Q_G	volumetric gas flow rate, (m^3/s)
Rg	gas constant
STF	surface tension factor, $(c/z)\cdot(d\sigma/dc)^2$, (kg^2·m^3/kmol·s^4)
r_b	bubble radius, (m)
T	inside diameter of STR, (m)
t	temperature, (°C)
vvm	volume of gas sparged per unit volume of the liquid per minute
W	baffle width, (m)
We	Weber number, ($N^2D^3\rho/\sigma$)
z	number of ions formed by dissociation of an electrolyte molecule

Greek Symbols

ε_G	fractional gas hold-up
ρ	density, (kg/m^3)
σ	surface tension, (N/m)
ψ	function of activity coefficient, $[1+(d\ln f/d\ln c)]^{-1}$

Subscripts

cd	complete dispersion
G	gas

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