J. Chem. Eng. Data **1998,** *43,* 128−132

Density, Viscosity, and Surface Tension of Sodium Carbonate + Sodium Bicarbonate Buffer Solutions in the Presence of Glycerine, Glucose, and Sucrose from 25 to 40 °C

Gonzalo Vázquez,[†] Estrella Alvarez,[*,‡] and José M. Navaza[†]

Department of Chemical Engineering, University of Santiago, Spain, and Department of Chemical Engineering, University of Vigo, Spain

The density, viscosity, and surface tension of 0.5 M sodium carbonate + 0.5 M sodium bicarbonate buffer solutions in the presence of glycerin, glucose, or sucrose were measured at temperatures from 25 °C to 40 °C. The concentration ranges were (0−187.2) g·dm^{-3} for glycerin, (0−264) g·dm^{-3} for glucose, and (0−204) g·dm^{-3} for sucrose. The experimental values were correlated with the concentration of the organic component. The maximum deviations were always less than 0.5%.

Introduction

The absorption of CO_2 in sodium carbonate + sodium bicarbonate buffer solutions is frequently used for determining the mass-transfer parameters in gas−liquid processes. The rate at which these processes occur depends on the mass-transfer coefficient, the interfacial area, and, when the gas reacts chemically with the liquid, on the corresponding kinetic constant.

For the design of the gas−liquid contactors, it is necessary to know the mass-transfer coefficients and the effective interfacial area. Both parameters can be determined by some of the chemical methods proposed in the literature (Danckwerts, 1970; Shumpe and Deckwer, 1980; Linek and Vacek, 1981; and Westerterp, 1990). Danckwerts' method, based on the absorption of CO_2 in buffer solutions (often sodium carbonate + bicarbonate buffer), has been the most used method in our previous studies (Vázquez et al., 1992, 1994).

The application of this method requires the knowledge of certain physical properties: the density, viscosity, and surface tension of the liquid phase and the solubility and diffusivity of the gas in the liquid. The knowledge of the physical properties is also important to determine the diffusivity through the equations that relate it to the viscosity (Joosten and Danckwerts, 1972; Hikita et al., 1979; Ratcliff and Holdcroft, 1963), as well as to analyze the influence of the viscosity and surface tension on the interfacial area and the mass-transfer coefficients. In our previous studies of the influence of the viscosity and surface tension on interfacial area (Vázquez et al., 1993, 1994, 1996), we have controlled these variables by addition of sodium dodecyl sulfate, sugars, or glycerine.

This paper reports the experimental values of the density, viscosity, and surface tension of sodium carbonate + sodium bicarbonate buffer solutions over the temperature range (25−40) °C, in the presence of various concentrations of glycerin, glucose or sucrose. The concentration of the sodium carbonate and of the sodium bicarbonate has been maintained constant at 0.5 mol·dm^{-3}, and the organic component concentration ranges were (0−2.035) mol·dm^{-3} for glycerin, (0−1.328) mol·dm^{-3} for glucose, and (0−0.6) mol·dm^{-3} for sucrose. These concentrations and temperatures are the same as those were used in the absorption processes.

Table 1. Density of 0.5 M Sodium Carbonate + 0.5 M Sodium Bicarbonate Buffer Solutions with and without Glycerin, Glucose, or Sucrose

organic component	c/(mol·dm^{-3})	ρ/(kg·m^{-3})			
		t = 25 °C	t = 30 °C	t = 35 °C	t = 40 °C
without glycerin	0.000	1075.70	1072.40	1070.80	1068.70
	0.114	1079.10	1075.30	1073.50	1071.10
	0.261	1082.30	1078.60	1077.10	1074.40
	0.408	1086.10	1082.40	1080.30	1078.00
	0.598	1089.80	1086.60	1084.30	1082.10
	0.789	1094.60	1091.30	1088.90	1086.30
	0.978	1099.00	1095.60	1093.10	1090.60
	1.109	1102.20	1098.40	1096.20	1093.90
	1.400	1109.10	1105.60	1103.30	1100.80
	1.800	1119.00	1115.40	1113.20	1110.30
	2.000	1123.90	1120.80	1118.00	1115.50
	2.035	1124.60	1121.20	1118.80	1116.20
glucose	0.083	1081.80	1078.60	1076.70	1074.40
	0.168	1088.00	1084.50	1082.60	1080.10
	0.248	1093.50	1090.00	1088.10	1085.60
	0.337	1099.50	1096.20	1093.90	1091.50
	0.444	1106.40	1103.10	1101.10	1099.10
	0.574	1115.00	1112.10	1109.60	1107.30
	0.942	1140.20	1137.20	1134.50	1132.40
	1.200	1157.60	1156.10	1152.70	1150.50
	1.328	1166.80	1165.40	1161.90	1159.60
sucrose	0.047	1081.90	1079.10	1077.20	1075.10
	0.094	1088.20	1085.20	1083.20	1081.20
	0.146	1095.00	1092.10	1089.70	1088.10
	0.205	1102.60	1099.40	1097.30	1095.30
	0.251	1108.40	1105.30	1103.20	1101.10
	0.313	1115.90	1113.20	1111.00	1109.20
	0.395	1126.40	1123.70	1121.60	1119.50
	0.500	1139.90	1137.30	1135.20	1133.30
	0.600	1152.60	1150.50	1148.60	1146.80

Experimental Section

All the sodium carbonate + sodium bicarbonate buffer solutions, with and without glycerin, glucose, or sucrose,

---

[*] To whom correspondence should be adressed. Postal address: Department of Chemical Engineering, E.T.S.E.I., 36200-Vigo, Spain. E-mail: ealvarez@uvigo.es.

[†] University of Santiago.

[‡] University of Vigo.

S0021-9568(97)00197-0 CCC: $15.00

Table 2. Dynamic Viscosity of 0.5 M Sodium Carbonate + 0.5 M Sodium Bicarbonate Buffer Solutions with and without Glycerin, Glucose, or Sucrose

organic component	c/(mol·dm^{-3})	η/(mPa·s)			
		t = 25 °C	t = 30 °C	t = 35 °C	t = 40 °C
without glycerin	0.000	1.2474	1.1149	1.0028	0.9031
	0.114	1.2781	1.1407	1.0271	0.9285
	0.261	1.3270	1.1853	1.0716	0.9663
	0.408	1.3811	1.2391	1.1214	1.0177
	0.598	1.4596	1.3174	1.1942	1.0853
	0.789	1.5496	1.3968	1.2746	1.1607
	0.978	1.6388	1.4861	1.3569	1.2386
	1.109	1.7066	1.5526	1.4193	1.2974
	1.400	1.8634	1.6993	1.5565	1.4316
	1.800	2.0876	1.9121	1.7652	1.6302
	2.000	2.2075	2.0248	1.8708	1.7264
	2.035	2.2288	2.0471	1.9012	1.7468
glucose	0.083	1.2926	1.1527	1.0369	0.9327
	0.168	1.3548	1.2071	1.0846	0.9761
	0.248	1.4241	1.2650	1.1369	1.0179
	0.337	1.5066	1.3369	1.1977	1.0748
	0.444	1.6127	1.4249	1.2799	1.1462
	0.574	1.7488	1.5427	1.3857	1.2366
	0.942	2.1818	1.9105	1.7129	1.5212
	1.200	2.5142	2.2004	1.9598	1.7424
	1.328	2.6843	2.3362	2.1027	1.8545
sucrose	0.047	1.3002	1.1608	1.0438	0.9384
	0.094	1.3703	1.2229	1.1006	0.9897
	0.146	1.4598	1.3034	1.1659	1.0508
	0.205	1.5738	1.4027	1.2532	1.1287
	0.251	1.6703	1.4851	1.3264	1.1953
	0.313	1.8027	1.6025	1.4281	1.2883
	0.395	2.0002	1.7684	1.5724	1.4177
	0.500	2.2437	1.9912	1.7673	1.5961
	0.600	2.4888	2.2138	1.9642	1.7714

Table 3. Surface Tension of 0.5 M Sodium Carbonate + 0.5 M Sodium Bicarbonate Buffer Solutions with and without Glycerin, Glucose, or Sucrose

organic component	c/(mol·dm^{-3})	σ/(mN·m^{-1})			
		t = 25 °C	t = 30 °C	t = 35 °C	t = 40 °C
without glycerin	0.000	75.01	74.63	74.17	73.73
	0.114	74.81	74.46	74.02	73.59
	0.261	74.66	74.30	73.88	73.45
	0.408	74.42	74.08	73.69	73.26
	0.598	74.23	73.86	73.45	73.04
	0.789	74.06	73.66	73.24	72.82
	0.978	73.81	73.45	73.08	72.65
	1.109	73.73	73.36	72.97	72.56
	1.400	73.46	73.13	72.70	72.31
	1.800	73.18	72.82	72.40	72.04
	2.000	73.06	72.71	72.29	71.92
	2.035	73.02	72.68	72.26	71.88
glucose	0.083	75.31	74.93	74.45	74.01
	0.168	75.60	75.20	74.73	74.23
	0.248	75.82	75.41	74.94	74.46
	0.337	76.06	75.62	75.14	74.68
	0.444	76.27	75.84	75.36	74.87
	0.574	76.52	76.07	75.57	75.12
	0.942	77.04	76.58	76.09	75.65
	1.200	77.28	76.86	76.41	75.94
	1.328	77.44	76.98	76.56	76.07
sucrose	0.047	75.23	74.83	74.37	73.93
	0.094	75.41	75.02	74.56	74.12
	0.146	75.62	75.19	74.74	74.31
	0.205	75.81	75.38	74.94	74.52
	0.251	75.94	75.51	75.08	74.66
	0.313	76.10	75.67	75.25	74.84
	0.395	76.32	75.85	75.45	75.06
	0.500	76.52	76.05	75.67	75.30
	0.600	76.69	76.24	75.86	75.48

were prepared with distilled–deionized water. The solutes were Merck products of nominal purity >99.5% for glycerin and 99.95% for glucose and sucrose. Sodium carbonate and sodium bicarbonate, Probus products, were both >99.9% pure. All the solutions were prepared by mass with deviations of less than ±0.2% from the desired concentrations. The physical properties were measured at temperatures ranging from (25 to 40) °C at 5 °C intervals.

The density was measured using 25-cm^3 pycnometers of the Gay-Lussac type. The pycnometers containing the solutions were placed in a thermostated bath maintained constant to ±0.05 °C. Then they were weighed with a Mettler AJ150 balance with a precision of ±0.0001 g. Each density value was the average of at least five measurements (maximum deviations from the average were always less than 0.01%), and the accuracy of these measuments was ±0.004 kg·m^{-3}.

The kinematic viscosity was determined from the transit time of the liquid meniscus through a capillary (0.46-mm diameter) measured with a precision of ±0.01 s in a Shott-Geräte AVS 350 automatic Ubbelohde viscometer. The viscometer was immersed in a bath controlled to ±0.05 °C. Each measurement was repeated at least 10 times with a maximum deviation of less than 0.4%. The dynamic viscosity was calculated by multiplying the kinematic viscosity by the corresponding density. The dynamic viscosity of the sodium carbonate + sodium bicarbonate solutions also was determined using a ball viscosimeter and a Broofield Synchrometer LVT rotating viscosimeter.

The pycnometers and the viscometer were calibrated with distilled–deionized water. The measured values for water were compared with those existing in the literature (Marsh, 1987), the deviations being less than 0.1%.

The surface tension of the aqueous solutions was measured using a Traube stalagmometer, by means of the equation

$$\sigma = K(\rho/N) \qquad (1)$$

where K is the constant of calibration of the stalagmometer, ρ the density of the liquid, and N the number of drops of liquid. The stalagmometer was calibrated with distilled–deionized water. The surface tension of pure water was determined with a Prolabo tensiometer, which employs the Wilhelmy plate principle (Van der Bogaert et al., 1980; Lin et al., 1990). The detailed experimental procedure has been described elsewhere (Vazquez et al., 1995). In general, each surface-tension value reported was an average of 5 to 10 measurements, where the maximum deviations from the average value were always less than 0.5%. The solutions were thermostated with a precision of ±0.05 °C and the accuracy of the measurements was ±0.02 mN·m^{-1}.

Results and Discussion

The density, viscosity and surface tension of the sodium carbonate + sodium bicarbonate buffer solutions, sodium carbonate + sodium bicarbonate + glycerin, sodium carbonate + sodium bicarbonate + glucose, and sodium carbonate + sodium bicarbonate + sucrose, at (25, 30, 35, and 40) °C, are listed in Tables 1–3. The density, viscosity, and surface tension decrease upon increasing the temperature. For each temperature the density and viscosity of the solutions increase with increasing glycerin, glucose, or sucrose concentration as shown in Figures 1 and 2. The surface tension increases with increasing glucose or sucrose concentration and reduces with increasing the glycerin concentration Figure 3).

The density of solutions of the organic component in 0.5 M sodium carbonate + 0.5 M sodium bicarbonate buffer, ρ, was expressed as a function of the concentration of the

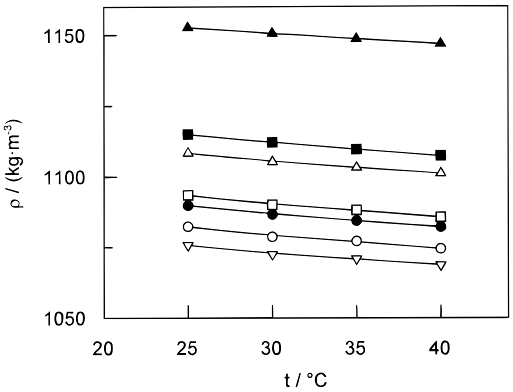

Figure 1. Density of solutions of organic component in 0.5 M sodium carbonate + 0.5 M sodium bicarbonate buffer as a function of temperature: (▽) buffer solution, (○) glycerin 0.261 mol·dm^{-3}, (●) glycerin 0.598 mol·dm^{-3}, (□) glucose 0.248 mol·dm^{-3}, (■) glucose 0.574 mol·dm^{-3}, (△) sucrose 0.251 mol·dm^{-3}, (▲) sucrose 0.600 mol·dm^{-3}.

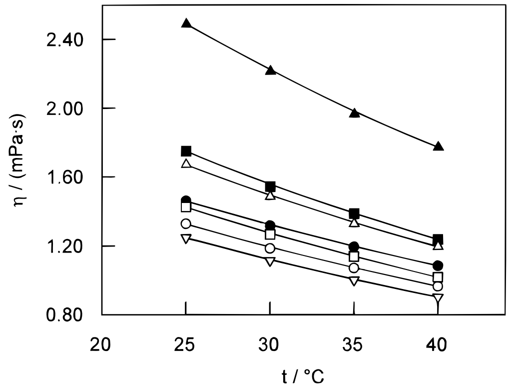

Figure 2. Viscosity of solutions of organic component in 0.5 M sodium carbonate + 0.5 M sodium bicarbonate buffer as a function of temperature: (▽) buffer solution, (○) glycerin 0.261 mol·dm^{-3}, (●) glycerin 0.598 mol·dm^{-3}, (□) glucose 0.248 mol·dm^{-3}, (■) glucose 0.574 mol·dm^{-3}, (△) sucrose 0.251 mol·dm^{-3}, (▲) sucrose 0.600 mol·dm^{-3}.

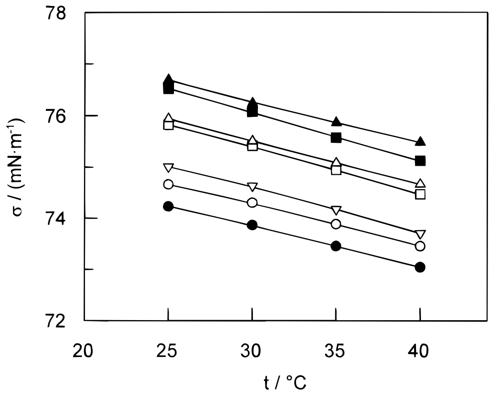

Figure 3. Surface tension of solutions of organic component in 0.5 M sodium carbonate + 0.5 M sodium bicarbonate buffer as a function of temperature: (▽) buffer solution, (○) glycerin 0.261 mol·dm^{-3}, (●) glycerin 0.598 mol·dm^{-3}, (□) glucose 0.248 mol·dm^{-3}, (■) glucose 0.574 mol·dm^{-3}, (△) sucrose 0.251 mol·dm^{-3}, (▲) sucrose 0.600 mol·dm^{-3}.

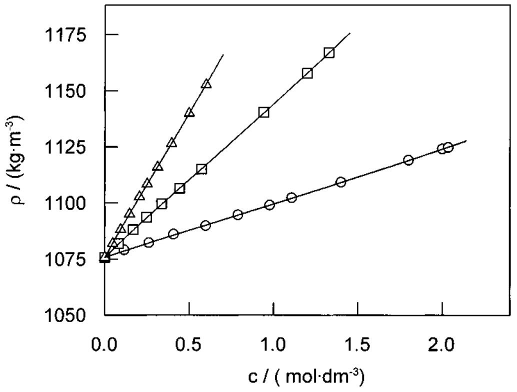

Figure 4. Density of solutions of organic component in 0.5 M sodium carbonate + 0.5 M sodium bicarbonate buffer at 25 °C plotted against the organic component concentration: (○) glycerin, (□) glucose, (△) sucrose, (—) calculated from eq 2.

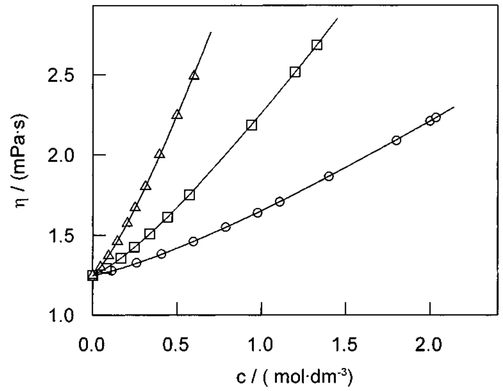

Figure 5. Viscosity of solutions of organic component in 0.5 M sodium carbonate + 0.5 M sodium bicarbonate buffer at 25 °C plotted against the organic component concentration: (○) glycerin, (□) glucose, (△) sucrose, (—) calculated from eq 3.

Table 4. Density Parameters A_2, A_3, and A_4 (Eq 2)

organic component	t/°C	A_2	A_3	A_4
glycerin	25	27.722	−7.403	3.404
	30	26.184	−5.835	3.073
	35	24.457	−4.464	2.716
	40	23.025	−3.197	2.406
glucose	25	81.135	−26.516	13.531
	30	78.720	−21.856	11.846
	35	74.634	−16.738	9.971
	40	71.754	−12.227	8.167
sucrose	25	148.504	−56.904	39.941
	30	144.616	−47.632	37.893
	35	140.397	−41.035	35.369
	40	137.164	−34.814	33.428

Table 5. Viscosity Parameter m (Eq 3)

organic component	t/°C			
	25	30	35	40
glycerin	0.4040	0.3830	0.3650	0.3470
glucose	1.0070	0.8570	0.7630	0.6680
sucrose	2.3690	2.0820	1.8180	1.6420

organic component by an empirical equation of the form (Choudary et al., 1994)

$$\rho/(\mathrm{kg{\cdot}m^{-3}}) = \rho_0/(\mathrm{kg{\cdot}m^{-3}}) + \sum_{i=2}^{4} A_i\{c/(\mathrm{mol{\cdot}dm^{-3}})\}^{i/2} \qquad (2)$$

where ρ_0 is the density in absence of organic component (given by sodium carbonate (0.5 mol·dm^{-3}) + sodium bicarbonate (0.5 mol·dm^{-3}) buffer solutions), c is the concentration of glycerin, glucose, or sucrose, and A_i are the adjustable coefficients whose values are listed in Table 4.

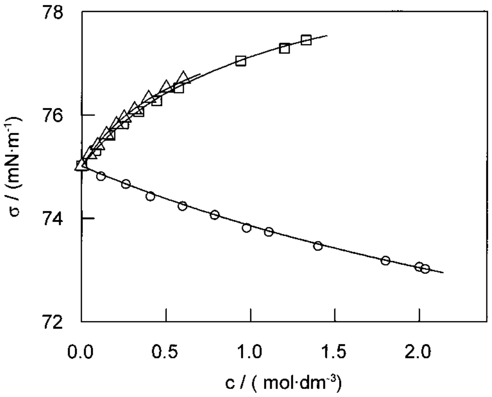

Figure 6. Surface tension of solutions of organic component in 0.5 M sodium carbonate + 0.5 M sodium bicarbonate buffer at 25 °C plotted against the organic component concentration: (○) glycerin, (□) glucose, (△) sucrose, (—) calculated from eq 4.

Table 6. Surface Tension Parameters B_1 and B_2 (Eq 4)

organic component		t/°C			
		25	30	35	40
glycerin	B_1	14.942	12.304	9.612	7.616
	B_2	0.218	0.183	0.146	0.119
glucose	B_1	80.581	73.375	66.668	59.121
	B_2	1.017	0.931	0.849	0.754
sucrose	B_1	121.804	95.682	79.278	69.959
	B_2	1.553	1.221	1.008	0.887

Table 7. Parameters of Eq 5 for the Temperature Dependence of the Adjustable Coefficients in Eq 2 (A_2, A_3, and A_4), in Eq 3 (m), and in Eq 4 (B_1 and B_2)

organic component	$f(t)$	a_0	a_1	a_2
glycerin	A_2	36.7152	−105.2338	79.0876
	A_3	−17.4029	129.8637	−224.5789
	A_4	5.2932	−22.0350	15.6683
	m	0.5284	−1.5651	2.2383
	B_1	33.7345	−248.7577	479.0021
	B_2	0.4656	−3.2450	5.9689
glucose	A_2	92.7434	−93.5074	−346.9408
	A_3	−52.0518	288.5966	−111.1703
	A_4	21.3376	−77.0256	−88.7870
	m	2.1097	−15.8345	41.0360
	B_1	112.6476	−327.8046	−254.4232
	B_2	1.3617	−3.1603	−6.7150
sucrose	A_2	174.2394	−325.1933	488.7016
	A_3	−123.7326	939.7700	−2276.3792
	A_4	52.0955	−139.5278	79.8337
	m	4.7047	−33.0648	82.8181
	B_1	375.6719	−3922.6300	12536.8700
	B_2	4.7672	−49.5412	157.4291

The maximum deviation of the estimated density from the experimental density is ±0.1 $\mathrm{kg \cdot m^{-3}}$. The comparison between the experimental densities and those calculated by means of eq 2 at 25 °C are shown graphically in Figure 4.

The variation of dynamic viscosity with the concentration was expressed by a empirical equation of the form

$$\eta/(\mathrm{mPa \cdot s}) = \eta_0/(\mathrm{mPa \cdot s}) + m\{c/(\mathrm{mol \cdot dm^{-3}})\}^n \qquad (3)$$

where η is the viscosity of the solution, η_0 is the viscosity in the absence of an organic component, and c is the concentration of the organic component. The parameter n was optimized using all the data and takes the value of 1.25, and the values of the fitted parameter m are listed in Table 5.

The experimental and estimated viscosity at 25 °C are compared in Figure 5. Maximum differences are always less than 0.5%.

The surface tension was correlated with the concentration of the organic component by fitting the following equation

$$\sigma = \frac{\sigma_0 + B_1 c/(\mathrm{mol \cdot dm^{-3}})}{1 + B_2 c/(\mathrm{mol \cdot dm^{-3}})} \qquad (4)$$

where σ is the surface tension of the solution, σ_0 is the surface tension of the buffer solution, c is the concentration of glycerin, glucose, or sucrose, and B_1 and B_2 are fitted parameters whose values are shown in Table 6.

The surface tensions calculated by means of eq 4 present a maximum deviation with respect to the experimental ones of less than 0.1%. The experimental and calculated surface tension, at 25 °C, are graphically compared in Figure 6.

The dependence of the density, dynamic viscosity, and surface tension with the temperature can be modeled by treating the adjustable coefficients in eqs 2−4 as functions of the temperature of the form

$$f(t) = \sum_{i=0}^{2} a_i \left(\frac{t/°\mathrm{C}}{273.15}\right)^i \qquad (5)$$

where $f(t)$ represents the adjustable coefficients in eqs 2−4 and a_i are the fitted parameters whose values are listed in Table 7.

Literature Cited

Camacho, F.; Paez, M. P.; Blázquez, G.; Garrido, J. M. Oxygen Absorption in Alkaline Sodium Dithionite Solutions. *Chem. Eng. Sci.* **1992**, *47*, 4309−4314.

Choudary, N. V.; Jasra, R. V. Densities of Aqueous Solutions of Sodium Bisulfite and Sodium 2-Methylallyl Sulfate. *J. Chem. Eng. Data* **1994**, *39*, 181−183.

Danckwerts, P. V. *Gas−Liquid Reactions*; McGraw-Hill Book Co.: New York, 1970.

Hikita, H.; Asai, S.; Ishikama, H.; Seko, M.; Kitajima, H. Diffusivities of Carbon Dioxide in Aqueous Mixed Electrolyte Solutions. *Chem. Eng. J.* **1979**, *17*, 77−80.

Joosten, G. E. H.; Danckwerts, P. V. Solubility and Diffusivity of Nitrous Oxide in Equimolar Potassium Carbonate−Potassium Bicarbonate Solutions at 25 °C and 1 Atm. *J. Chem. Eng. Data* **1972**, *17*, 452−454.

Lin, S. Y.; McKeigue, K.; Mandarelli, C. Diffusion-Controlled Surfactant Adsorption Studied by Pendant Drop Digitalization. *AIChE J.* **1990**, *36*, 1785−1793.

Linek, V.; Vacek, K. V. Chemical Engineering Use of Catalyzed Sulfite Oxidation Kinetics for the Determination of Mass Transfer Characteristics of Gas−Liquid Contactors. *Chem. Eng. Sci.* **1981**, *36*, 1747−1768.

Marsh, K. N. *Recommemded Reference Materials for the Realization of Physicochemical Properties*; Blackwell Scientific Publications: Oxford, 1987.

Oyevaar, M. H.; Westerterp, K. R. The Use of Chemical Method for the Determination of Interfacial Areas in Gas−Liquid Contactors. *Chem. Eng. Sci.* **1989**, *44*, 2691−2701.

Ratcliff, G. A.; Holdcroft, J. G. Diffusivities of Gases in Aqueous Electrolyte Solutions. *Trans. Inst. Chem. Eng. (London)*, **1963**, *41*, 315−319.

Schumpe, A.; Deckwer, W. D. Analysis of Chemical Methods for Determination of Interfacial Areas in Gas−Liquid Dispersions with Non-Uniform Bubble Sizes. *Chem. Eng. Sci.* **1980**, *35*, 2221−2233.

Van der Bogaert, R.; Joos, P. Diffusion-Controlled Adsorption Kinetics for a Mixture of Surface Active Agents at the Solution−Air Interface. *J. Phys. Chem.* **1980**, *84*, 190−194.

Vázquez, G.; Chenlo, F.; Navaza, J. M.; Alvarez, E.; Caeiro, F. Reaction of the Commercial Sugar in the Absorption of CO_2 in Carbonate−Bicarbonate Buffer Solutions. *An. Quim.* **1992**, *88*, 223−229.

Vázquez, G.; Antorrena, G.; Navaza, J. M.; Santos, V.; Rodríguez, T. Absorption of CO_2 in Aqueous Solutions of Various Viscosities in the Presence of Induced Turbulence. *Int. Chem. Eng.* **1993**, *33*, 649−655.

Vázquez, G.; Antorrena, G.; Navaza, J. M.; Santos, V. Effective Interfacial Area in the Presence of Induced Turbulence. *Int. Chem. Eng.* **1994**, *34*, 247−254.

Vázquez, G.; Alvarez, E.; Navaza, J. M. Surface Tension of Alcohol + Water from 20 to 50 °C. *J. Chem. Eng. Data.* **1995**, *40*, 611−614.

Vázquez, G.; Antorrena, G.; Navaza, J. M.; Santos, V. Absorption of CO_2 by Water and Surfactant Solutions in the Presence of Induced Marangoni Effect. *Chem. Eng. Sci.* **1996**, *51*, 3317−3324.

Received for review August 15, 1997. Accepted January 20, 1998. This work has been partially financed by the DGICYT (Spain) (Grant PB94-0626).

JE970197J