

Density, Viscosity, and Surface Tension of Aqueous Solutions of Sodium Sulfite and Sodium Sulfite + Sucrose from 25 to 40 °C

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The density, viscosity, and surface tension of aqueous solutions of sodium sulfite and sodium sulfite + sucrose were measured at temperatures from 25 to 40 °C. The concentration ranges were 0–0.5 mol·dm⁻³ for sodium sulfite and 0–171 g·dm⁻³ for sucrose. The experimental values were correlated with the concentration of sucrose. The maximum deviation was always less than 0.5%.

Introduction

The effective interfacial area is a variable of importance in the design of gas–liquid reactors. In the determination of interfacial areas the sulfite method is frequently used, which is based on the absorption of O₂ in aqueous solutions of sodium sulfite in the presence of a catalyzer (Schumpe et al., 1980; Linek et al., 1981). The influence of the physical properties on the interfacial area can be studied by addition to the liquid phase of certain substances which modifies it, such as sucrose. The addition of sucrose, glucose, or glycerin was used in a previous paper (Vázquez et al., 1993) to study the influence of viscosity on gas–liquid absorption.

The objective of this work, as a necessary preliminary to further work on mass transfer, was to measure the density, viscosity, and surface tension of aqueous solutions of sodium sulfite over the temperature range 25–40 °C. The concentration ranges considered in this work were 0–0.5 mol·dm⁻³ for sodium sulfite and 0–171 g·dm⁻³ for sucrose (which equate to concentrations used in the absorption processes).

Experimental Section

Aqueous solutions of sodium sulfite and sodium sulfite + sucrose were prepared with distilled–deionized water. The solutes were Merck products of nominal purity >99.8% for sodium sulfite and 99.95% for sucrose. 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 of the sodium sulfite and sodium sulfite + sucrose solutions was measured using 25 cm³ (at 20 °C) pycnometers of the Gay–Lussac type. The pycnometers containing the solutions were thermostated to maintain a constant temperature with a precision of ±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%.

Table 1. Density, Viscosity, and Surface Tension of the Aqueous Solutions of Sodium Sulfite

C/(mol·dm ⁻³)	t/°C	ρ/(kg·m ⁻³)	η/(mPa·s)	σ/(mN·m ⁻¹)
0.000	25	997.0	0.8900	72.01
	30	995.6	0.7973	71.23
	35	994.0	0.7255	70.43
	40	992.2	0.6529	69.52
0.100	25	1007.2	0.9396	72.58
	30	1006.0	0.8484	72.03
	35	1004.5	0.7629	71.50
0.200	40	1002.7	0.6921	70.98
	25	1015.8	0.9805	72.73
	30	1014.6	0.8851	72.18
0.300	35	1012.8	0.7955	71.63
	40	1011.0	0.7217	71.11
	25	1025.3	1.0321	72.88
0.400	30	1023.9	0.9255	72.35
	35	1022.3	0.8335	71.78
	40	1020.5	0.7563	71.27
	25	1035.0	1.0877	73.01
0.500	30	1033.7	0.9798	72.49
	35	1032.1	0.8803	71.96
	40	1030.1	0.7970	71.41
	25	1044.7	1.1398	73.15
0.500	30	1043.4	1.0213	72.64
	35	1041.7	0.9143	72.13
	40	1039.9	0.8266	71.56

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. The precision of the temperature control in all these measurements was ±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 pycnometers and the viscometer were calibrated with distilled–deionized water. The measured density and kinematic viscosity of water at the working temperatures, all of which were within 0.2% of published values (Marsh, 1987), are listed in Table 1.

The surface tension of the aqueous solutions of sodium sulfite and sodium sulfite + sucrose was measured using a Traube stalagmometer, by means of the equation

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

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Table 2. Density, Viscosity, and Surface Tension of the Aqueous Solutions of Sodium Sulfite (0.1 M) + Sucrose

$C/(\text{mol}\cdot\text{dm}^{-3})$	$t/^\circ\text{C}$	$\rho/(\text{kg}\cdot\text{m}^{-3})$	$\eta/(\text{mPa}\cdot\text{s})$	$\sigma/(\text{mN}\cdot\text{m}^{-1})$
0.047	25	1013.9	0.9396	72.64
	30	1012.4	0.8484	72.09
	35	1010.8	0.7629	71.56
0.146	40	1009.2	0.6921	71.05
	25	1028.0	0.9633	72.79
	30	1026.6	0.8673	72.26
0.205	35	1024.9	0.7806	71.74
	40	1023.3	0.7182	71.22
	25	1036.7	1.0514	72.91
0.251	30	1035.3	0.9475	72.37
	35	1033.6	0.8974	71.85
	40	1032.0	0.8219	71.33
0.313	25	1043.2	1.1708	72.00
	30	1042.0	1.0573	72.47
	35	1040.3	0.9450	71.94
0.395	40	1038.6	0.8580	71.43
	25	1052.3	1.2517	73.13
	30	1051.2	1.1271	72.61
0.500	35	1049.4	1.0071	72.08
	40	1047.6	0.9180	71.56
	25	1064.0	1.3671	73.33
0.146	30	1062.9	1.2355	72.82
	35	1061.2	1.1005	72.28
	40	1059.3	0.9993	71.75
0.205	25	1078.9	1.5256	73.66
	30	1077.5	1.3859	73.12
	35	1075.7	1.2329	72.59
0.251	40	1073.9	1.1210	72.03

Table 3. Density, Viscosity, and Surface Tension of the Aqueous Solutions of Sodium Sulfite (0.2 M) + Sucrose

$C/(\text{mol}\cdot\text{dm}^{-3})$	$t/^\circ\text{C}$	$\rho/(\text{kg}\cdot\text{m}^{-3})$	$\eta/(\text{mPa}\cdot\text{s})$	$\sigma/(\text{mN}\cdot\text{m}^{-1})$
0.047	25	1023.6	1.0094	72.79
	30	1022.6	0.9108	72.25
	35	1020.8	0.8160	71.70
0.146	40	1018.7	0.7419	71.19
	25	1038.6	1.1057	72.96
	30	1037.5	1.0014	72.42
0.205	35	1035.7	0.8985	71.87
	40	1033.6	0.8180	71.37
	25	1047.4	1.1756	73.06
0.251	30	1046.2	1.0671	72.53
	35	1044.5	0.9567	72.99
	40	1042.5	0.8735	71.46
0.313	25	1054.1	1.2383	73.15
	30	1052.8	1.1221	72.63
	35	1051.1	1.0089	72.09
0.395	40	1049.2	0.9212	71.59
	25	1063.4	1.3247	73.29
	30	1062.0	1.2029	72.76
0.500	35	1060.3	1.0827	72.23
	40	1058.5	0.9894	71.74
	25	1075.6	1.4481	73.50
0.146	30	1074.0	1.3186	72.96
	35	1072.3	1.1877	72.44
	40	1070.7	1.0852	71.95
0.205	25	1091.7	1.6216	73.83
	30	1090.3	1.4793	73.27
	35	1088.6	1.3371	72.75
0.251	40	1086.9	1.2200	72.25

where K is the constant of the 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 (Bogaert et al., 1980; Lin et al., 1990). The measured values for water (Table 1) were compared with those existing in the literature (Marsh, 1987), the deviations being less than 0.1%.

The solutions were thermostated with a precision of ± 0.05 °C. The surface tension value reported was an

Table 4. Density, Viscosity, and Surface Tension of the Aqueous Solutions of Sodium Sulfite (0.3 M) + Sucrose

$C/(\text{mol}\cdot\text{dm}^{-3})$	$t/^\circ\text{C}$	$\rho/(\text{kg}\cdot\text{m}^{-3})$	$\eta/(\text{mPa}\cdot\text{s})$	$\sigma/(\text{mN}\cdot\text{m}^{-1})$
0.047	25	1032.9	1.0636	72.94
	30	1031.9	0.9549	72.41
	35	1030.3	0.8642	71.85
0.146	40	1028.2	0.7842	71.34
	25	1048.5	1.1718	73.11
	30	1047.2	1.0537	72.57
0.205	35	1045.7	0.9604	72.03
	40	1043.7	0.8757	71.52
	25	1057.9	1.2466	73.23
0.251	30	1056.4	1.1233	72.69
	35	1054.9	1.0263	72.14
	40	1053.1	0.9405	71.63
0.313	25	1065.1	1.3122	73.32
	30	1063.3	1.1854	72.78
	35	1062.0	1.0840	72.25
0.395	40	1060.3	0.9945	71.73
	25	1074.7	1.4040	73.47
	30	1072.8	1.2717	72.91
0.500	35	1071.4	1.1638	72.39
	40	1070.0	1.0686	71.87
	25	1087.7	1.5385	73.70
0.146	30	1085.8	1.3896	73.12
	35	1084.3	1.2760	72.60
	40	1082.8	1.1758	72.09
0.205	25	1104.0	1.7209	74.03
	30	1102.6	1.5611	73.43
	35	1101.0	1.4311	72.93
0.251	40	1099.1	1.3217	72.41

Table 5. Density, Viscosity, and Surface Tension of the Aqueous Solutions of Sodium Sulfite (0.4 M) + Sucrose

$C/(\text{mol}\cdot\text{dm}^{-3})$	$t/^\circ\text{C}$	$\rho/(\text{kg}\cdot\text{m}^{-3})$	$\eta/(\text{mPa}\cdot\text{s})$	$\sigma/(\text{mN}\cdot\text{m}^{-1})$
0.047	25	1041.7	1.1148	73.08
	30	1040.3	1.0084	72.55
	35	1038.8	0.9043	72.03
0.146	40	1036.7	0.8183	71.49
	25	1056.9	1.2241	73.25
	30	1055.4	1.1083	72.71
0.205	35	1053.8	0.9922	72.20
	40	1051.9	0.9007	71.66
	25	1066.0	1.3060	73.36
0.251	30	1064.5	1.1813	72.82
	35	1062.8	1.0575	72.32
	40	1060.9	0.9635	71.78
0.313	25	1073.2	1.3742	73.47
	30	1071.7	1.2413	72.91
	35	1069.9	1.1194	72.42
0.395	40	1068.1	1.0180	71.88
	25	1082.6	1.4754	73.62
	30	1081.2	1.3331	73.05
0.500	35	1079.3	1.2021	72.57
	40	1077.6	1.0970	72.03
	25	1095.2	1.6207	73.85
0.146	30	1093.7	1.4579	73.26
	35	1091.7	1.3248	72.79
	40	1089.8	1.2134	72.26
0.205	25	1111.2	1.8271	74.22
	30	1109.5	1.6351	73.59
	35	1107.4	1.5005	73.13
0.251	40	1105.1	1.3797	72.61

average of at least five measurements, where the maximum deviations from the average value were always less than 0.4%.

Results and Discussion

The density, viscosity, and surface tension of the aqueous solutions of sodium sulfite and sodium sulfite + sucrose, at 25, 30, 35, and 40 °C, are listed in Tables 1–6. For each temperature the density, viscosity, and surface tension of the solutions increase with increasing sucrose concentration, Figures 1–3.

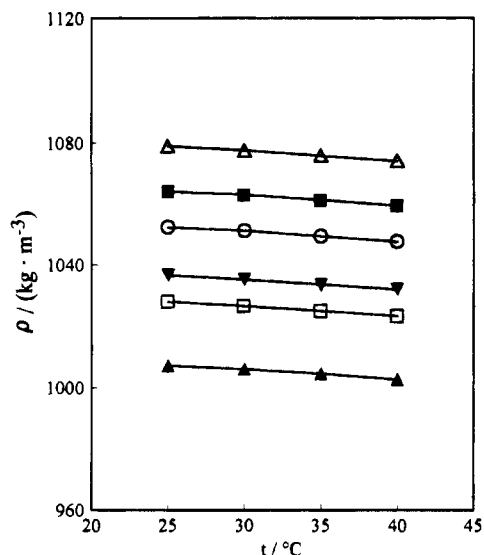


Figure 1. Experimental densities of the aqueous solutions of sodium sulfite (0.1 M) + sucrose as a function of temperature: (▲) 0 mol·dm⁻³ sucrose; (□) 0.146 mol·dm⁻³ sucrose; (▼) 0.205 mol·dm⁻³ sucrose; (○) 0.313 mol·dm⁻³ sucrose; (■) 0.395 mol·dm⁻³ sucrose; (Δ) 0.5 mol·dm⁻³ sucrose.

Table 6. Density, viscosity and surface tension of the aqueous solutions of sodium sulfite (0.5 M) + sucrose

$C/(\text{mol}\cdot\text{dm}^{-3})$	$t/^\circ\text{C}$	$\rho/(\text{kg}\cdot\text{m}^{-3})$	$\eta/(\text{mPa}\cdot\text{s})$	$\sigma/(\text{mN}\cdot\text{m}^{-1})$
0.047	25	1051.6	1.1687	73.22
	30	1050.2	1.0473	72.70
	35	1048.5	0.9380	72.20
	40	1046.8	0.8479	71.64
0.146	25	1066.8	1.2843	73.39
	30	1065.4	1.1468	72.86
	35	1063.7	1.0308	72.37
	40	1061.8	0.9362	71.81
0.205	25	1076.0	1.3712	73.52
	30	1074.6	1.2249	72.96
	35	1072.9	1.1041	72.49
	40	1071.0	1.0026	71.93
0.251	25	1083.3	1.4475	73.63
	30	1081.8	1.2893	73.06
	35	1080.2	1.1640	72.60
	40	1078.4	1.0589	72.04
0.313	25	1093.1	1.5594	73.78
	30	1091.7	1.3909	73.21
	35	1090.1	1.2510	72.75
	40	1088.1	1.1423	72.20
0.395	25	1105.8	1.7233	74.03
	30	1104.5	1.5325	73.41
	35	1102.9	1.3806	72.99
	40	1100.8	1.2613	72.44
0.500	25	1121.9	1.9613	74.42
	30	1120.5	1.7374	73.77
	35	1119.0	1.5650	73.36
	40	1117.2	1.4372	72.81

The density of the sodium sulfite + sucrose solutions, ρ , was expressed as a function of the concentration of sucrose by an empirical equation of the form (Choudary et al., 1994)

$$\rho/(\text{kg}\cdot\text{m}^{-3}) = \rho_d/(\text{kg}\cdot\text{m}^{-3}) + \sum_{i=2}^4 A_i (C/(\text{mol}\cdot\text{dm}^{-3}))^{i/2} \quad (2)$$

where ρ_d is the density in the absence of sucrose (given by the 0.1, 0.2, 0.3, 0.4, or 0.5 mol·dm⁻³ sulfite solutions), C is the concentration of sucrose, and A_i are the adjustable coefficients whose values are listed in Table 7.

The maximum deviation of the estimated density from the experimental density is $\pm 0.1 \text{ kg}\cdot\text{m}^{-3}$. The comparison

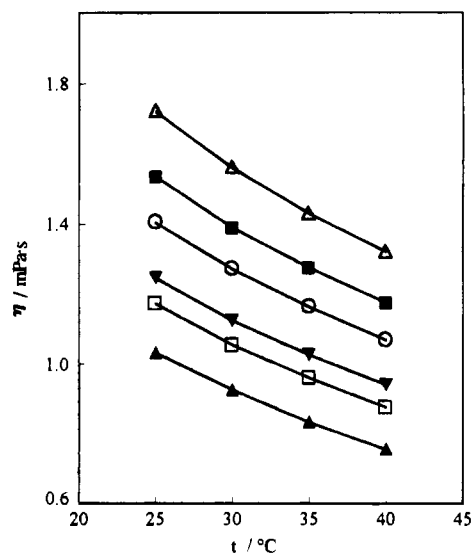


Figure 2. Experimental viscosities of the aqueous solutions of sodium sulfite (0.3 M) + sucrose as a function of temperature: (▲) 0 mol·dm⁻³ sucrose; (□) 0.146 mol·dm⁻³ sucrose; (▼) 0.205 mol·dm⁻³ sucrose; (○) 0.313 mol·dm⁻³ sucrose; (■) 0.395 mol·dm⁻³ sucrose; (Δ) 0.5 mol·dm⁻³ sucrose.

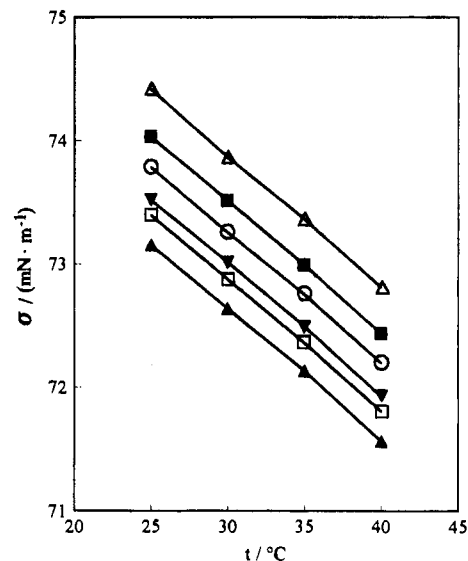


Figure 3. Experimental surface tensions of the aqueous solutions of sodium sulfite (0.5 M) + sucrose as a function of temperature: (▲) 0 mol·dm⁻³ sucrose; (□) 0.146 mol·dm⁻³ sucrose; (▼) 0.205 mol·dm⁻³ sucrose; (○) 0.313 mol·dm⁻³ sucrose; (■) 0.395 mol·dm⁻³ sucrose; (Δ) 0.5 mol·dm⁻³ sucrose.

between the experimental densities and those calculated by means of eq 2 at 25 °C are graphically shown in Figure 4.

The variation of the dynamic viscosity of the sodium sulfite + sucrose solutions with the concentration was expressed through the following equation:

$$\eta/(\text{mPa}\cdot\text{s}) = \eta_d/(\text{mPa}\cdot\text{s}) + m(C/(\text{mol}\cdot\text{dm}^{-3}))^n \quad (3)$$

where η is the viscosity of the solution, η_d is the viscosity in the absence of sucrose, and C is the concentration of sucrose. The values of the fitted parameters m and n are listed in Table 8.

The experimental and estimated viscosities at 30 °C are compared in Figure 5. The maximum differences are always less than 0.5%.

Table 7. Parameters of eq 2 for the Sucrose Concentration Dependence of the Density of the Aqueous Solutions of Sodium Sulfite + Sucrose

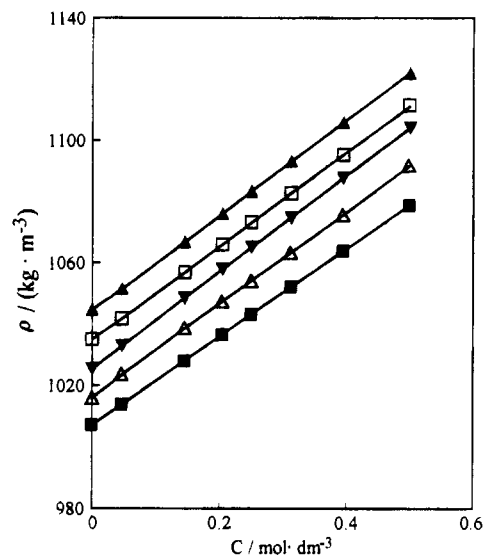
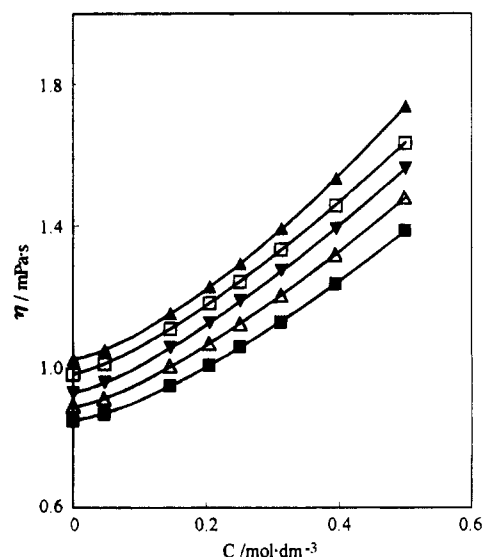
$C/(\text{mol}\cdot\text{dm}^{-3})$	$t/^\circ\text{C}$	A_2	A_3	A_4
0.100	25	135.298	29.506	-25.603
	30	118.792	86.683	-74.234
	35	114.811	96.123	-80.782
	40	125.767	61.398	-53.613
0.200	25	179.667	-87.494	67.860
	30	195.501	-143.115	114.083
	35	193.600	-135.751	107.834
	40	179.991	-92.847	74.786
0.300	25	162.727	-11.309	5.359
	30	185.893	-99.983	84.417
	35	184.234	-88.858	71.941
	40	163.422	-12.969	5.797
0.400	25	136.238	52.152	-41.383
	30	128.396	76.796	-62.190
	35	132.189	61.640	-50.980
	40	125.775	91.954	-81.590
0.500	25	133.044	68.175	-53.765
	30	128.764	80.223	-62.561
	35	128.063	82.743	-63.967
	40	133.987	58.760	-42.045

Table 8. Parameters of eq 3 for the Sucrose Concentration Dependence of the Viscosity of the Aqueous Solutions of Sodium Sulfite + Sucrose

$C/(\text{mol}\cdot\text{dm}^{-3})$	$t/^\circ\text{C}$	m	n
0.100	25	1.4892	1.3442
	30	1.4012	1.3846
	35	1.2359	1.3949
	40	1.1265	1.3931
0.200	25	1.6087	1.3294
	30	1.4932	1.3312
	35	1.3827	1.3521
	40	1.2531	1.3288
0.300	25	1.7047	1.3088
	30	1.5645	1.3024
	35	1.4340	1.2649
	40	1.3532	1.2590
0.400	25	1.9137	1.3725
	30	1.6410	1.3256
	35	1.6300	1.3972
	40	1.5446	1.4097
0.500	25	2.2006	1.4263
	30	1.9109	1.4182
	35	1.7060	1.3931
	40	1.6081	1.4011

Table 9. Parameters of Eq 4 for the Sucrose Concentration Dependence of the Surface Tension of the Aqueous Solutions of Sodium Sulfite + Sucrose

$C/(\text{mol}\cdot\text{dm}^{-3})$	$t/^\circ\text{C}$	a	b	d
0.100	25	72.579	-0.772	-54.678
	30	72.027	-0.669	-46.723
	35	71.494	-0.630	-43.571
	40	70.973	-0.553	-37.720
0.200	25	72.729	-0.764	-54.195
	30	72.178	-0.617	-43.059
	35	71.624	-0.611	-42.164
	40	71.112	-0.548	-37.330
0.300	25	72.874	-0.730	-51.710
	30	72.345	-0.697	-48.996
	35	71.776	-0.648	-44.947
	40	71.266	-0.633	-43.542
0.400	25	73.009	-0.775	-55.080
	30	72.485	-0.757	-53.506
	35	71.960	-0.738	-51.635
	40	71.414	-0.722	-50.024
0.500	25	73.150	-0.819	-58.456
	30	72.633	-0.802	-56.890
	35	72.131	-0.797	-55.990
	40	71.562	-0.771	-53.627

**Figure 4.** Density of the aqueous solutions of sodium sulfite + sucrose at 25 °C plotted against the sucrose concentration: (■) 0.1 mol dm⁻³ sodium sulfite; (△) 0.2 mol dm⁻³ sodium sulfite; (▼) 0.3 mol dm⁻³ sodium sulfite; (□) 0.4 mol dm⁻³ sodium sulfite; (▲) 0.5 mol dm⁻³ sodium sulfite; (—) calculated from eq 2.**Figure 5.** Viscosity of the aqueous solutions of sodium sulfite + sucrose at 30 °C plotted against the sucrose concentration: (■) 0.1 mol dm⁻³ sodium sulfite; (△) 0.2 mol dm⁻³ sodium sulfite; (▼) 0.3 mol dm⁻³ sodium sulfite; (□) 0.4 mol dm⁻³ sodium sulfite; (▲) 0.5 mol dm⁻³ sodium sulfite; (—) calculated from eq 3.

The surface tension of the sodium sulfite + sucrose solution was correlated with the concentration of sucrose by fitting the following equation:

$$\sigma = \frac{1 + aC/(\text{mol}\cdot\text{dm}^{-3})}{b + dC/(\text{mol}\cdot\text{dm}^{-3})} \quad (4)$$

where σ is the surface tension of the solution, C is the concentration of sucrose, and a , b , and d are fitted parameters whose values are shown in Table 9.

The values of the surface tension estimated by means of eq 4 present a maximum deviation with respect to the experimental ones of less than 0.1%. The experimental and

Literature Cited

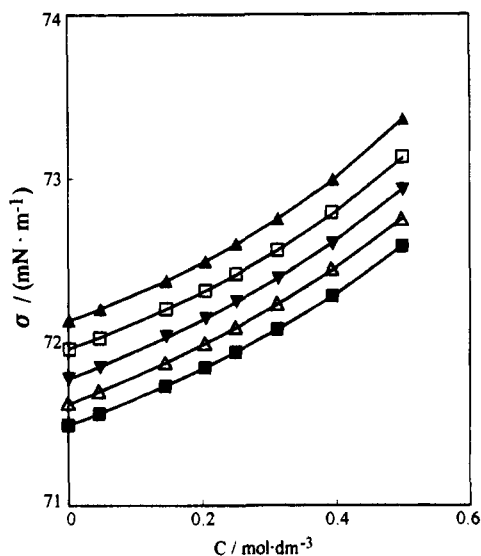


Figure 6. Surface tension of the aqueous solutions of sodium sulfite + sucrose at 35 °C plotted against the sucrose concentration: (■) 0.1 mol dm⁻³ sodium sulfite; (△) 0.2 mol dm⁻³ sodium sulfite; (▼) 0.3 mol dm⁻³ sodium sulfite; (□) 0.4 mol dm⁻³ sodium sulfite; (▲) 0.5 mol dm⁻³ sodium sulfite; (—) calculated from eq 4.

calculated surface tensions, at 35 °C, are graphically compared in Figure 6.

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