Viscosity of Binary and Ternary Aqueous Systems of NaH_2PO_4, Na_2HPO_4, Na_3PO_4, KH_2PO_4, K_2HPO_4, and K_3PO_4

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The kinematic viscosities of aqueous solutions of NaH_2PO_4, Na_2HPO_4, Na_3PO_4, KH_2PO_4, K_2HPO_4, and K_3PO_4, and of their pH-buffering ternary systems, were measured at various concentrations and at temperatures between 293.1 K and 323.1 K. Those of the single-solute solutions were correlated with concentration and temperature, and those of the ternary system with temperature, with deviations less than 1.2% and 0.5%, respectively.

Introduction

Studies of gas−liquid mass transfer are frequently facilitated by using aqueous buffers so as to be able to work at constant pH and hence simplify mathematical modeling of the results. Since knowledge of the viscosity of the liquid phase is also generally essential for modeling the experimental results, it is necessary to know the viscosities of the buffer solutions.

When the absorbed gas reacts with some component of the liquid phase, it is common to use sodium or potassium carbonate + bicarbonate buffers (Benadda et al., 1994; Alper, 1981) or sodium or potassium phosphate buffers (Joosten and Danckwerts, 1973; Alper and Deckwer, 1980). The latter are also of biotechnological relevance, being used in determining the kinetics of microbial wastewater treatments (Hunik et al., 1993) and in microbial fermentation of paper industry waste (Kitpreechavanich et al., 1984; Lindén and Hanhn-Hägerdal, 1989). In previous papers ´zquez et al., 1994a, 1994b) we reported viscosity data for sodium carbonate + bicarbonate buffers with and without a variety of sugars. Since previously published viscosity data for phosphate solutions are only sporadic, failing to provide systematic coverage of a wide range of concentrations and temperatures, we now report the kinematic viscosities of solutions of sodium and potassium phosphates.

Specifically, we studied aqueous solutions of NaH_2PO_4, HPO_4, Na_3PO_4, KH_2PO_4, K_2HPO_4, and K_3PO_4, and of all the pH-buffering binary combinations of these salts. The concentrations of the single-solute solutions varied from 0 dm^{-3} to about 1.2 $mol{\cdot}dm^{-3}$ (or to the limit of solubility) by steps of either approximately 0.1 $mol{\cdot}dm^{-3}$ or approximately 0.2 $mol{\cdot}dm^{-3}$ (depending on solubility). The binary solutions were nominal (0.2 + 0.2) $mol{\cdot}dm^{-3}$ and (0.4 + 0.4) $mol{\cdot}dm^{-3}$ equimolar mixtures at 298.1 K (these concentrations cover the range mentioned in the literature cited above; higher concentrations are prevented by solubility limits, and lower concentrations have viscosities very close to that of water; and in any case, the pH of these buffers varies little with their concentration so long as equimolarity is maintained). All these solutions were studied at temperatures ranging in 5 K steps from 293.1 K to 323.1 K. The accuracy of the viscosity measurements was greater than that usually required in mass transfer studies.

Experimental Section

Solutions were prepared using degassed distilled water and Merck salts with nominal purities >98% (>99.7% for NaH_2PO_4, Na_2HPO_4, KH_2PO_4, and K_2HPO_4); salts were dried to constant mass (Budavari, 1989) in an A&D Instruments AD 4712 IR balance. The solutions were prepared by mass using a Mettler AJ 150 balance with a precision of ±0.0001 g and were filtered before use (maximum deviations from nominal values were less than 0.1%).

Kinematic viscosities were determined in a Schott-Geräte AVS 350 automatic Ubbelohde viscosimeter, using the experimental protocol described elsewhere (Vázquez et al., 1994a, 1994b). All measurements were quintuplicated, and values deviating by more than 0.2% from the mean were discarded. Densities were measured at 298.1 K in a Bosch S2000/30 densitometric balance with an accuracy of $\pm 0.0001\ g{\cdot}cm^{-3}$ (maximum deviations from nominal values were less than 0.02%), and pH was measured at the same temperature with a Schott-Geräte CG841 pH-meter with a precision of ±0.001 units (maximum deviations from nominal values were less than 0.2%). The precision of the temperature control in all measurements was ±0.1 K).

Results

Table 1 lists the measured kinematic viscosities of aqueous solutions of NaH_2PO_4, Na_2HPO_4, Na_3PO_4, KH_2PO_4, K_2HPO_4, and K_3PO_4 at various concentrations (expressed as mass fractions w) and temperatures. Densities measured at 298.1 K are included in Table 2.

Table 3 lists the measured kinematic viscosities of the ternary systems $Na_3PO_4 + Na_2HPO_4$, $Na_3PO_4 + NaH_2PO_4$, $Na_3PO_4 + K_2HPO_4$, $Na_3PO_4 + KH_2PO_4$, $Na_2HPO_4 + NaH_2PO_4$, $Na_2HPO_4 + K_3PO_4$, $Na_2HPO_4 + KH_2PO_4$, $NaH_2PO_4 + K_3PO_4$, $NaH_2PO_4 + K_2HPO_4$, $K_3PO_4 + K_2HPO_4$, $K_3PO_4 + KH_2PO_4$, and $K_2HPO_4 + KH_2PO_4$ in water, at two different concentrations and various temperatures. pH at 298.1 K are also included. Densities measured at 298.1 K are included in Table 2.

The viscosity data for each single-solute solution were correlated with their mass concentration and temperature by means of the equation

$$\nu = \nu_0 + A e^{B/T^m} w^n \tag{1}$$

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S0021-9568(96)00074-X CCC: $12.00

Table 1. Kinematic Viscosities ν (10^{-6} $m^2 \cdot s^{-1}$) of Binary Systems of Various Mass Fractions w of Salts at Temperatures T

	w_A					
T/K	0.024 27	0.046 38	0.069 02	0.089 76	0.107 20	0.131 01
	NaH_2PO_4 (A) + H_2O (B)					
293.1	1.0628	1.1338	1.2056	1.2837	1.3726	1.4734
298.1	0.9533	1.0095	1.0740	1.1432	1.2113	1.2985
303.1	0.8584	0.9040	0.9626	1.0178	1.0852	1.1591
308.1	0.7739	0.8215	0.8695	0.9255	0.9785	1.0442
313.1	0.7011	0.7459	0.7895	0.8314	0.8842	0.9418
318.1	0.6430	0.6819	0.7253	0.7607	0.8056	0.8584
323.1	0.5849	0.6286	0.6644	0.6962	0.7425	0.7851

	w_A				
T/K	0.014 45	0.028 04	0.042 50	0.055 23	0.067 73
	Na_2HPO_4 (A) + H_2O (B)				
293.1	1.0495	1.1009	1.1612	1.2160	1.2758
298.1	0.9409	0.9802	1.0335	1.0874	1.1482
303.1	0.8410	0.8816	0.9315	0.9800	1.0331
308.1	0.7640	0.7989	0.8388	0.8807	0.9330
313.1	0.6930	0.7236	0.7574	0.7960	0.8437
318.1	0.6330	0.6614	0.6904	0.7236	0.7679
323.1	0.5857	0.6066	0.6333	0.6660	0.7043

	w_A				
/K	0.016 44	0.031 95	0.047 58	0.062 04	0.075 84
	Na_3PO_4 (A) + H_2O (B)				
293.1	1.0849	1.1695	1.2686	1.3771	1.5054
298.1	0.9652	1.0372	1.1274	1.2220	1.3341
303.1	0.8671	0.9282	1.0001	1.0947	1.1860
308.1	0.7840	0.8353	0.9019	0.9775	1.0651
313.1	0.7114	0.7681	0.8224	0.8867	0.9654
318.1	0.6514	0.6930	0.7463	0.8082	0.8783
323.1	0.5980	0.6348	0.6832	0.7382	0.7996

	w_A					
/K	0.026 85	0.052 39	0.077 46	0.101 50	0.124 69	0.147 11
	KH_2PO_4 (A) + H_2O (B)					
293.1	1.0453	1.0843	1.1292	1.1738	1.2275	1.2876
298.1	0.9329	0.9675	1.0054	1.0509	1.0952	1.1501
303.1	0.8347	0.8689	0.9019	0.9429	0.9882	1.0325
308.1	0.7560	0.7865	0.8190	0.8513	0.8911	0.9329
313.1	0.6866	0.7164	0.7439	0.7769	0.8129	0.8459
318.1	0.6303	0.6563	0.6790	0.7101	0.7442	0.7746
323.1	0.5749	0.5968	0.6259	0.6524	0.6859	0.7140

	w_A					
/K	0.033 91	0.066 31	0.097 46	0.126 21	0.153 89	0.181 00
	K_2HPO_4 (A) + H_2O (B)					
293.1	1.0604	1.1151	1.1821	1.2551	1.3361	1.4357
298.1	0.9464	0.9974	1.0599	1.1243	1.1954	1.2818
303.1	0.8510	0.9002	0.9502	1.0100	1.0828	1.1529
308.1	0.7699	0.8130	0.8621	0.9153	0.9787	1.0492
313.1	0.6993	0.7411	0.7886	0.8326	0.8932	0.9532
318.1	0.6418	0.6806	0.7217	0.7634	0.8159	0.8725
323.1	0.5871	0.6257	0.6642	0.7047	0.7548	0.8057

	w_A					
T/K	0.041 38	0.079 74	0.115 80	0.148 29	0.179 10	0.209 41
	K_3PO_4 (A) + H_2O (B)					
293.1	1.0754	1.1728	1.2863	1.4117	1.5617	1.7403
298.1	0.9585	1.0491	1.1401	1.2580	1.3855	1.5542
303.1	0.8608	0.9443	1.0301	1.1315	1.2554	1.3980
308.1	0.7796	0.8547	0.9339	1.0262	1.1326	1.2646
313.1	0.7094	0.7780	0.8483	0.9354	1.0303	1.1499
318.1	0.6483	0.7123	0.7722	0.8574	0.9457	1.0521
323.1	0.5966	0.6558	0.7165	0.7904	0.8701	0.9649

Table 2. Densities of Binary and Ternary Systems of Various Mass Fractions w at 298.1 K

w_A	ρ/kg·m^{-3}	w_A	ρ/kg·m^{-3}
NaH_2PO_4 (A) + H_2O (B)		Na_2HPO_4 (A) + H_2O (B)	
0.024 27	1017.1	0.014 45	1012.0
0.046 38	1033.7	0.028 04	1025.3
0.069 02	1050.8	0.042 50	1039.9
0.089 76	1067.1	0.055 23	1053.0
0.107 20	1080.7	0.067 73	1064.9
0.131 01	1096.5		
Na_3PO_4 (A) + H_2O (B)		KH_2PO_4 (A) + H_2O (B)	
0.016 44	1018.8	0.026 85	1018.8
0.031 95	1038.1	0.052 39	1037.9
0.047 58	1056.1	0.077 46	1056.2
0.062 04	1072.3	0.101 50	1074.1
0.075 84	1088.5	0.124 69	1090.9
		0.147 11	1109.2
K_2HPO_4 (A) + H_2O (B)		K_3PO_4 (A) + H_2O (B)	
0.033 91	1029.8	0.041 38	1044.9
0.066 31	1056.6	0.079 74	1083.7
0.097 46	1084.9	0.115 80	1123.0
0.126 21	1111.7	0.148 29	1158.5
0.153 89	1137.6	0.179 10	1195.6
0.181 00	1163.5	0.209 41	1231.3

w_A	w_B	ρ/kg·m^{-3}	w_A	w_B	ρ/kg·m^{-3}
Na_3PO_4 (A) + Na_2HPO_4 (B) + H_2O (C)					
0.029 33	0.025 39	1061.3	0.058 66	0.050 78	1118.2
Na_3PO_4 (A) + NaH_2PO_4 (B) + H_2O (C)					
0.029 88	0.021 87	1052.3	0.059 76	0.043 74	1097.6
Na_3PO_4 (A) + K_2HPO_4 (B) + H_2O (C)					
0.029 21	0.031 03	1064.7	0.058 41	0.062 06	1122.8
Na_3PO_4 (A) + KH_2PO_4 (B) + H_2O (C)					
0.029 69	0.024 64	1052.0	0.059 37	0.049 28	1104.6
Na_2HPO_4 (A) + NaH_2PO_4 (B) + H_2O (C)					
0.026 28	0.022 21	1041.7	0.052 56	0.044 43	1080.4
Na_2HPO_4 (A) + K_3PO_4 (B) + H_2O (C)					
0.025 23	0.047 33	1065.5	0.050 46	0.094 67	1125.4
Na_2HPO_4 (A) + KH_2PO_4 (B) + H_2O (C)					
0.026 21	0.025 12	1043.7	0.052 42	0.050 25	1083.4
NaH_2PO_4 (A) + K_3PO_4 (B) + H_2O (C)					
0.021 69	0.038 38	1055.1	0.043 3	0.076 76	1106.6
NaH_2PO_4 (A) + K_2HPO_4 (B) + H_2O (C)					
0.022 10	0.032 08	1045.2	0.044 19	0.064 16	1086.2
K_3PO_4 (A) + K_2HPO_4 (B) + H_2O (C)					
0.037 62	0.030 86	1067.3	0.075 23	0.061 72	1129.0
K_3PO_4 (A) + KH_2PO_4 (B) + H_2O (C)					
0.038 30	0.024 55	1057.0	0.076 60	0.049 10	1108.8
K_2HPO_4 (A) + KH_2PO_4 (B) + H_2O (C)					
0.032 02	0.025 02	1046.0	0.064 05	0.050 04	1087.9

where the temperature dependence of ν_0, the kinematic viscosity of water, is given (Vázquez et al., 1994a) by

$$\nu_0/\mathrm{m}^2\cdot\mathrm{s}^{-1} = 9.7734 \times 10^{-8} \mathrm{e}^{5.8662\times 10^7/(T/\mathrm{K})^3} \tag{2}$$

The parameters A, B, and n in eq 1 were optimized using the Nelder–Mead algorithm and are listed in Table 4. The deviations between the experimental data and the predictions of eq 1 are all less than 1.2%.

The viscosity data for the ternary systems were correlated with temperature by means of the equation (Vázquez et al., 1994a)

$$\nu = C\mathrm{e}^{D/T^m} \tag{3}$$

Table 3. Kinematic Viscosities ν (10^{-6} $m^2 \cdot s^{-1}$) and *pH* (at 298.1 K) of the Ternary Systems at Various Temperatures

	Na_3PO_4 (A) + Na_2HPO_4 (B) + H_2O (C)		Na_3PO_4 (A) + NaH_2PO_4 (B) + H_2O (C)	
T/K	$w_A = 0.029\ 33$ $w_B = 0.025\ 39$	$w_A = 0.058\ 66$ $w_B = 0.050\ 78$	$w_A = 0.029\ 88$ $w_B = 0.021\ 87$	$w_A = 0.059\ 76$ $w_B = 0.043\ 74$
293.1	1.2825	1.7557	1.2061	1.5387
298.1	1.1339	1.5487	1.0724	1.3534
303.1	1.0144	1.3767	0.9636	1.2027
308.1	0.9144	1.2312	0.8699	1.0807
313.1	0.8299	1.1074	0.7904	0.9792
318.1	0.7558	1.0053	0.7217	0.8922
323.1	0.6940	0.9163	0.6624	0.8230
pH	11.28	11.13	10.23	10.05

	Na_3PO_4 (A) + K_2HPO_4 (B) + H_2O (C)		Na_3PO_4 (A) + KH_2PO_4 (B) + H_2O (C)	
T/K	$w_A = 0.029\ 21$ $w_B = 0.031\ 03$	$w_A = 0.058\ 41$ $w_B = 0.062\ 06$	$w_A = 0.029\ 69$ $w_B = 0.024\ 64$	$w_A = 0.059\ 37$ $w_B = 0.049\ 28$
293.1	1.2289	1.5839	1.2042	1.4765
298.1	1.0872	1.3960	1.0705	1.3063
303.1	0.9735	1.2549	0.9630	1.1663
308.1	0.8858	1.1290	0.8708	1.0559
313.1	0.8022	1.0253	0.7925	0.9569
318.1	0.7350	0.9306	0.7243	0.8747
323.1	0.6739	0.8512	0.6675	0.8119
	11.39	11.30	10.25	10.12

	Na_2HPO_4 (A) + NaH_2PO_4 (B) + H_2O (C)		Na_2HPO_4 (A) + K_3PO_4 (B) + H_2O (C)	
	$w_A = 0.026\ 28$ $w_B = 0.022\ 21$	$w_A = 0.052\ 56$ $w_B = 0.044\ 43$	$w_A = 0.025\ 23$ $w_B = 0.047\ 33$	$w_A = 0.050\ 46$ $w_B = 0.094\ 67$
293.1	1.1761	1.3976	1.1964	1.4673
298.1	1.0486	1.2435	1.0627	1.3015
303.1	0.9428	1.1101	0.9534	1.1636
308.1	0.8485	0.9987	0.8636	1.0501
313.1	0.7755	0.9047	0.7864	0.9551
318.1	0.7093	0.8271	0.7196	0.8678
323.1	0.6474	0.7551	0.6606	0.7993
	6.52	6.37	11.41	11.32

	Na_2HPO_4 (A) + KH_2PO_4 (B) + H_2O (C)		NaH_2PO_4 (A) + K_3PO_4 (B) + H_2O (C)	
	$w_A = 0.026\ 21$ $w_B = 0.025\ 12$	$w_A = 0.052\ 42$ $w_B = 0.050\ 25$	$w_A = 0.021\ 69$ $w_B = 0.038\ 38$	$w_A = 0.043\ 39$ $w_B = 0.076\ 76$
293.1	1.1495	1.3245	1.1416	1.3101
298.1	1.0232	1.1708	1.0214	1.1714
303.1	0.9188	1.0491	0.9235	1.0516
308.1	0.8316	0.9437	0.8369	0.9515
313.1	0.7590	0.8568	0.7593	0.8631
318.1	0.6920	0.7840	0.6958	0.7907
323.1	0.6382	0.7196	0.6404	0.7247
pH	6.55	6.43	9.28	9.26

	NaH_2PO_4 (A) + K_2HPO_4 (B) + H_2O (C)		K_3PO_4 (A) + K_2HPO_4 (B) + H_2O (C)	
	$w_A = 0.022\ 10$ $w_B = 0.032\ 08$	$w_A = 0.044\ 19$ $w_B = 0.064\ 16$	$w_A = 0.037\ 62$ $w_B = 0.030\ 86$	$w_A = 0.075\ 23$ $w_B = 0.061\ 72$
293.1	1.1301	1.2707	1.1414	1.3200
298.1	1.0069	1.1327	1.0234	1.1803
303.1	0.9059	1.0199	0.9244	1.0642
308.1	0.8235	0.9218	0.8401	0.9612
313.1	0.7470	0.8375	0.7649	0.8776
318.1	0.6833	0.7682	0.7019	0.8054
323.1	0.6282	0.7060	0.6492	0.7412
pH	6.59	6.50	11.51	11.50

	K_3PO_4 (A) + KH_2PO_4 (B) + H_2O (C)		K_2HPO_4 (A) + KH_2PO_4 (B) + H_2O (C)	
T/K	$w_A = 0.038\ 30$ $w_B = 0.024\ 55$	$w_A = 0.076\ 60$ $w_B = 0.049\ 10$	$w_A = 0.032\ 02$ $w_B = 0.025\ 02$	$w_A = 0.064\ 05$ $w_B = 0.050\ 04$
293.1	1.1015	1.2493	1.0844	1.1998
298.1	0.9795	1.1290	0.9659	1.0726
303.1	0.8887	1.0147	0.8707	0.9636
308.1	0.8050	0.9204	0.7879	0.8736
313.1	0.7321	0.8417	0.7183	0.7951
318.1	0.6707	0.7724	0.6580	0.7267
323.1	0.6167	0.7104	0.6050	0.6683
pH	9.34	9.33	6.63	6.58

Table 4. Parameters of Eq 1, Giving the Kinematic Viscosity of Each of the Binary Systems Studied as a Function of Concentration and Temperature

$10^7 A/m^2 \cdot s^{-1}$	$10^{-7} B/K^3$	n
	NaH_2PO_4 (A) + H_2O (B)	
3.6557	6.6961	1.198
	Na_2HPO_4 (A) + H_2O (B)	
5.5566	6.3650	1.191
	Na_3PO_4 (A) + H_2O (B)	
8.1425	7.0151	1.274
	KH_2PO_4 (A) + H_2O (B)	
3.1280	5.6371	1.227
	K_2HPO_4 (A) + H_2O (B)	
3.0435	5.1736	1.310
	K_3PO_4 (A) + H_2O (B)	
8.6772	5.6288	1.531

Table 5. Parameters of Eq 3, Giving the Kinematic Viscosity of Each of the Ternary Systems Studied as a Function of Temperature

w_A	w_B	$10^7 C/m^2 \cdot s^{-1}$	$10^{-7} D/K^3$
	Na_3PO_4 (A) + Na_2HPO_4 (B) + H_2O (C)		
0.029 33	0.025 39	1.1420	6.0846
0.058 66	0.050 78	1.3484	6.4657
	Na_3PO_4 (A) + NaH_2PO_4 (B) + H_2O (C)		
0.029 88	0.021 87	1.1388	5.9436
0.059 76	0.043 74	1.2967	6.2161
	Na_3PO_4 (A) + K_2HPO_4 (B) + H_2O (C)		
0.029 21	0.031 03	1.1638	5.9265
0.058 41	0.062 06	1.3860	6.1310
	Na_3PO_4 (A) + KH_2PO_4 (B) + H_2O (C)		
0.029 69	0.024 64	1.1754	5.8562
0.059 37	0.049 28	1.3885	5.9401
	Na_2HPO_4 (A) + NaH_2PO_4 (B) + H_2O (C)		
0.026 28	0.022 21	1.1309	5.9002
0.052 56	0.044 43	1.2355	6.1123
	Na_2HPO_4 (A) + K_3PO_4 (B) + H_2O (C)		
0.025 23	0.047 33	1.1592	5.8730
0.050 46	0.094 67	1.3336	6.0359
	Na_2HPO_4 (A) + KH_2PO_4 (B) + H_2O (C)		
0.026 21	0.025 12	1.1295	5.8397
0.052 42	0.050 25	1.1963	6.0472
	NaH_2PO_4 (A) + K_3PO_4 (B) + H_2O (C)		
0.021 69	0.038 38	1.1674	5.7488
0.043 39	0.076 76	1.2729	5.8769
	NaH_2PO_4 (A) + K_2HPO_4 (B) + H_2O (C)		
0.022 10	0.032 08	1.1213	5.8188
0.044 19	0.064 16	1.2527	5.8348
	K_3PO_4 (A) + K_2HPO_4 (B) + H_2O (C)		
0.037 62	0.030 86	1.2265	5.6202
0.075 23	0.061 72	1.3558	5.7321
	K_3PO_4 (A) + KH_2PO_4 (B) + H_2O (C)		
0.038 30	0.024 55	1.1287	5.7363
0.076 60	0.049 10	1.3446	5.6250
	K_2HPO_4 (A) + KH_2PO_4 (B) + H_2O (C)		
0.032 02	0.025 02	1.0918	5.7795
0.064 05	0.050 04	1.1954	5.8113

The values of C and D calculated by Nelder−Mead optimization are listed in Table 5. The deviations between the experimental data and the predictions of eq 3 are all less than 0.5%.

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Received for review February 21, 1996. Accepted May 1, 1996.[⊗] This work was partly financed by the Spanish DGICYT (Grant PB94−0626).

JE960074J

[⊗] Abstract published in *Advance ACS Abstracts,* June 15, 1996.