Viscosities of Aqueous Solutions of Several Electrolytes Present in Sea Water

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Experimental viscosity and density measurements are reported on ternary solutions of several electrolytes present in sea water, and on a synthetic sea water over the range of ionic strength levels from 0.7 to 3.5 and for sea water up to a concentration factor of 3 and the temperature range from 25° to 150° C. The experimental viscosity data were correlated with a precision of 0.2 to 0.3%, assuming an additivity of the constants of the Othmer rule. Literature data were reviewed and compared with the correlation. Recommended sea water viscosity data are given as a function of temperature and concentration.

KNOWLEDGE of viscosities of sea water and brackish water brines, which contain primarily NaCl, KCl, Na_2SO_4, and $MgSO_4$, is important in the development and design of economic desalination processes. In a previous paper (*7*) the viscosities of the binary mixtures were evaluated on the basis of the Othmer rule or relation based on the properties of a reference substance under a similar condition. The reference substance was water and the single similar condition was temperature.

This paper presents viscosity measurements on ternary aqueous solutions and on calcium-free synthetic sea waters from 25° to 150° C., covering ionic strength concentration levels from 0.7 to 3.5. The experimental data were correlated with satisfactory precision, assuming an additivity of the constants of the Othmer rule.

The experimental apparatus, method, and calculation techniques have been given (*6, 7*).

EVALUATION OF EXPERIMENTAL DATA

Ternary Systems. The viscosity of a solution of a single salt was expressed by the Othmer rule (*11*):

$$\log \eta_{Si} = C_i + m_i \log \eta_w \tag{1a}$$

Similarly, the relative viscosity, which has some advantages and is more frequently used, can be given as:

$$\log \eta_{Ri} = A_{0i} + B_{0i} \log \eta_w \tag{1b}$$

where

η_{Ri} is the relative viscosity of the solution, η_{Si}/η_w

η_{Si} is the viscosity of the solution, cp.

η_w is the viscosity of water at the same temperature, cp.

$B_{0i} = m_i - 1$ and $A_{0i} = C_i$

A_{0i} and B_{0i} are temperature-independent Othmer constants for compound i for the linear equation. These constants were expressed as functions of ionic strength in molal units in the forms

$$A_{0i} = A_{1i}I + A_{2i}I^2 + A_{3i}I^3 \tag{2}$$

$$B_{0i} = B_{1i}I + B_{2i}I^2 + B_{3i}I^3 \tag{3}$$

To correlate the measured viscosities of two salts containing the Othmer constants of the mixture, A_M and B_M were calculated for each solution at three constant ionic strength levels over the entire test temperature range. Since the concentration of the solutions under our test conditions increased somewhat at high temperatures (this was caused by water evaporation into the vapor space of the closed viscometer system), the measured data were adjusted to constant ionic strength by graphical interpolation. Then, an attempt was made to plot the obtained A_M and B_M constants as a function of the mixture composition at each constant ionic strength level. The composition of the mixture was expressed as ionic strength fraction with respect to the salt components. Figures 1, 2, and 3 show the A_M and B_M values plotted against the ionic strength fraction of NaCl (X_{NaCl}) for the NaCl-KCl, NaCl-Na_2SO_4, and NaCl-$MgSO_4$ systems. The experimental data fell on the line connecting the A_0 and B_0 values of the pure compounds for the first two systems, thus confirming the additivity of these values. The A_M and B_M values, therefore, can be calculated from:

$$A_M = A_{01}\frac{I_1}{I_T} + A_{02}\frac{I_2}{I_T} \tag{4}$$

$$B_M = B_{01}\frac{I_1}{I_T} + B_{02}\frac{I_2}{I_T} \tag{5}$$

where

A_{01} and B_{01} are the Othmer constants of compound 1

A_{02} and B_{02} are the Othmer constants of compound 2

I_1 and I_2 are the ionic strengths of the compounds

I_T is the total ionic strength of the solution

The constant values derived from measurements in binary systems are given in Table I. In the NaCl-$MgSO_4$ system the experimental A_M and B_M values fell below the linear relationship, which is most apparent at high ionic strength. Thus, these mixtures seem to behave like mixtures containing more NaCl and less $MgSO_4$ than was actually the case. This behavior was attributed to the partial dissociation of $MgSO_4$ into its ions, which reduces the ionic strength of $MgSO_4$. To compensate for this, the dissociation constants given by Marshall (*9*) over the 0° to 200° C. temperature range were used. This calculation is rather lengthy. The activity coefficients must be used and the results can be obtained only by an iterative technique. Therefore, the results of the exact calculation were expressed in a simplified

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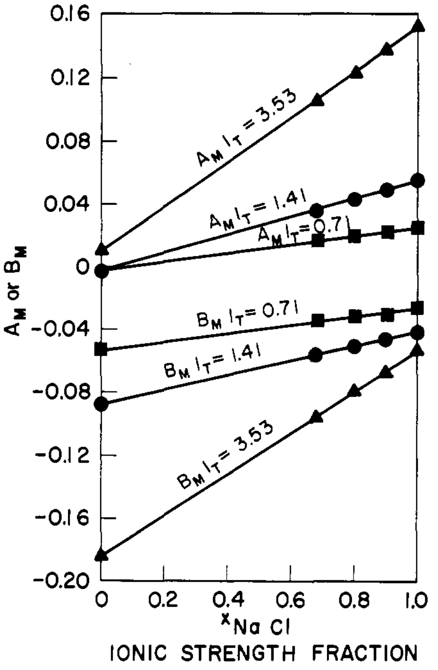

Figure 1. A_M and B_M values for the NaCl-KCl system

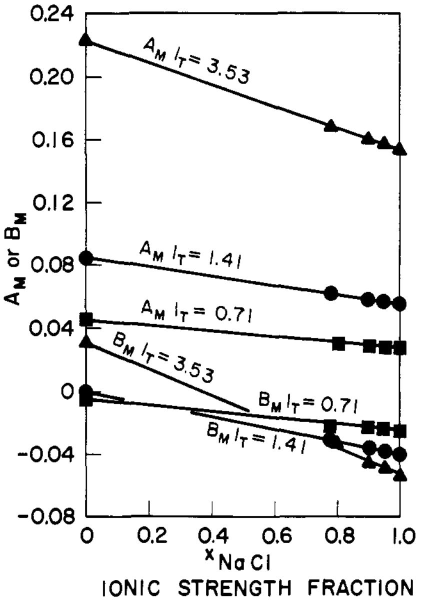

Figure 2. A_M and B_M values for the NaCl-Na₂SO₄ system

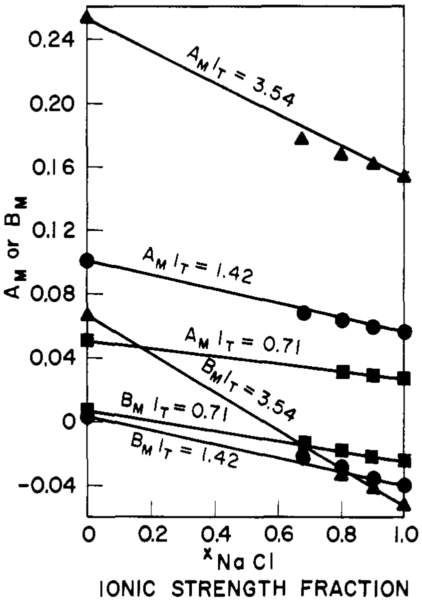

Figure 3. A_M and B_M values in the NaCl-MgSO₄ system

form, to yield the corrected $MgSO_4$ ionic strength. The calculated degrees of dissociation of $MgSO_4$ in simulated sea water at concentration factors of 1 and 3 and at 25° and 150° C., respectively, ranged from 72.7 to 73.0%; an average value of 0.728 was used in the concentration adjustment. The corrected ionic strength fractions of NaCl and $MgSO_4$ were expressed as:

$$X_{NaCl} = \frac{I_{NaCl}}{I_T - I_{MgSO_4}(1 - \alpha)} \tag{6}$$

and

$$X_{MgSO_4} = 1 - X_{NaCl} \tag{7}$$

where

$\alpha = 0.728$, degree of dissociation

The average deviations of the calculated A_M and B_M constants, from the experimentally determined values were:

For additivity. ±0.30%
For the exact method. ±0.10%
For the approximate method. ±0.10%

The deviations in the constants usually compensate one another.

The experimental data and calculated results are summarized in Tables II, III, and IV for the three systems investigated. The standard deviations of the calculated and experimental viscosity values for these systems are:

NaCl-KCl system. 0.27%
NaCl-Na_2SO_4 system. 0.27%
NaCl-$MgSO_4$ system. 0.38%

The simplified technique used to take into consideration the dissociation of magnesium sulfate with a fixed degree of dissociation (72.8%) can be applied only to sea water, its concentrates, and sea water-like solutions. For solutions of entirely different concentration and composition, the exact calculation must be used.

Calcium-Free Sea Water. The ionic composition of normal sea water as reported by Spiegler (*14*) is listed at the left of Table V. The ionic composition converted into salt composition is given at the right with two minor changes. The bicarbonate content was replaced by equivalent sulfate ions, and the potassium content was slightly reduced to balance the anions.

To avoid experimental difficulties caused by $CaSO_4$ precipitation at higher temperatures, $MgCl_2$ was substituted for $CaCl_2$. This calcium-free synthetic sea water with the given composition and four of its concentrates were prepared for the viscosity measurements. In calculating the sea water viscosities the ions were grouped as shown in the last column of Table V. Here it was assumed that all SO_4^{2-} was present as $MgSO_4$, and the small quantity of KBr was added to the NaCl content. In this way the synthetic sea water was reduced to a mixture of only four components: NaCl, $MgCl_2$, $MgSO_4$, and KCl.

The constant values used in the calculation are given in Table I. The constants for $MgCl_2$ and $CaCl_2$ solutions

Table I. Constants for Correlation of Viscosity by the Othmer Rule (Equations 2 and 3)

Compound	A_1	A_2	A_3	B_1	B_2	B_3
NaCl	0.03550	0.00231	−0.00003	−0.04753	0.01598	−0.00194
KCl	−0.00522	0.00175	0.00016	−0.09677	0.03215	−0.00547
Na_2SO_4	0.06672	−0.00721	0.00176	−0.01547	0.01356	−0.00189
$MgSO_4$	0.07341	−0.00278	0.00063	−0.01104	0.03467	−0.00740
$MgCl_2$	0.05508	−0.00045	0.00050	−0.00682	0.01614	−0.00217
$CaCl_2$	0.04241	−0.00051		−0.01450		

Table II. Relative Viscosities and Densities of Ternary Aqueous NaCl–KCl Solutions

Temp., °C.	Molality		Ionic Strength NaCl + KCl	Density	ν, Cs.	η_R	
	NaCl	KCl				Exptl.	Calcd.
25	0.6362	0.0707	0.7069	1.0257	0.9178	1.057	1.059
	1.2724	0.1414	1.4138	1.0521	0.9493	1.122	1.125
	3.1810	0.3535	3.5345	1.1243	1.0967	1.385	1.387
	0.5655	0.1414	0.7069	1.0259	0.9115	1.050	1.052
	1.1310	0.2828	1.4138	1.0529	0.9362	1.107	1.111
	2.8275	0.7070	3.5345	1.1255	1.0587	1.338	1.344
	0.4807	0.2262	0.7069	1.0262	0.9036	1.042	1.044
	0.9614	0.4524	1.4138	1.0538	0.9209	1.090	1.094
	2.4034	1.1311	3.5345	1.1274	1.0158	1.286	1.295
40	0.6362	0.0707	0.7069	1.0202	0.6837	1.069	1.068
	1.2724	0.1414	1.4138	1.0460	0.7124	1.142	1.141
	3.1810	0.3535	3.5345	1.1171	0.8274	1.416	1.416
	0.5655	0.1414	0.7069	1.0204	0.6796	1.062	1.062
	1.1310	0.2828	1.4138	1.0468	0.7039	1.129	1.128
	2.8275	0.7070	3.5345	1.1184	0.8029	1.376	1.378
	0.4807	0.2262	0.7069	1.0207	0.6746	1.055	1.056
	0.9614	0.4524	1.4138	1.0477	0.6939	1.114	1.113
	2.4034	1.1311	3.5345	1.1202	0.7750	1.330	1.333
60	0.6362	0.0707	0.7069	1.0108	0.4980	1.079	1.079
	1.2724	0.1414	1.4138	1.0363	0.5222	1.160	1.159
	3.1810	0.3535	3.5345	1.1064	0.6103	1.447	1.448
	0.5655	0.1414	0.7069	1.0111	0.4955	1.074	1.074
	1.1310	0.2828	1.4138	1.0372	0.5170	1.149	1.147
	2.8275	0.7070	3.5345	1.1078	0.5952	1.413	1.415
	0.4807	0.2262	0.7069	1.0114	0.4924	1.068	1.068
	0.9614	0.4524	1.4138	1.0380	0.5108	1.137	1.134
	2.4034	1.1311	3.5345	1.1097	0.5778	1.375	1.377
75	0.6375	0.0708	0.7083	1.0024	0.4097	1.085	1.086
	1.2749	0.1417	1.4166	1.0285	0.4316	1.173	1.170
	3.1869	0.3541	3.5411	1.0983	0.5060	1.469	1.470
	0.5666	0.1417	0.7083	1.0028	0.4079	1.081	1.081
	1.1333	0.2833	1.4166	1.0291	0.4273	1.162	1.160
	2.8329	0.7083	3.5412	1.0998	0.4940	1.436	1.440
	0.4816	0.2267	0.7083	1.0033	0.4053	1.075	1.076
	0.9632	0.4533	1.4165	1.0298	0.4226	1.150	1.148
	2.4078	1.1332	3.5410	1.1014	0.4819	1.403	1.405
100	0.6393	0.0710	0.7103	0.9865	0.3130	1.095	1.095
	1.2787	0.1421	1.4208	1.0126	0.3311	1.189	1.186
	3.1957	0.3551	3.5508	1.0827	0.3904	1.499	1.501
	0.5683	0.1421	0.7104	0.9867	0.3116	1.090	1.092
	1.1366	0.2842	1.4207	1.0132	0.3283	1.179	1.178
	2.8408	0.7102	3.5510	1.0843	0.3824	1.470	1.476
	0.4830	0.2273	0.7104	0.9873	0.3101	1.086	1.088
	0.9660	0.4546	1.4206	1.0139	0.3254	1.170	1.167
	2.4144	1.1363	3.5507	1.0859	0.3748	1.443	1.447
125	0.6429	0.0714	0.7144	0.9682	0.2528	1.103	1.103
	1.2862	0.1429	1.4291	0.9947	0.2679	1.201	1.201
	3.2130	0.3570	3.5700	1.0661	0.3173	1.525	1.529
	0.5715	0.1429	0.7144	0.9684	0.2515	1.097	1.101
	1.1431	0.2858	1.4289	0.9954	0.2659	1.193	1.193
	2.8563	0.7141	3.5704	1.0677	0.3118	1.500	1.509
	0.4858	0.2286	0.7145	0.9690	0.2505	1.094	1.097
	0.9714	0.4572	1.4286	0.9962	0.2639	1.185	1.184
	2.4274	1.1424	3.5698	1.0692	0.3063	1.476	1.484
150	0.6495	0.0722	0.7217	0.9477	0.2135	1.115	1.111
	1.2996	0.1444	1.4440	0.9750	0.2261	1.214	1.214
	3.2448	0.3606	3.6054	1.0485	0.2684	1.550	1.557
	0.5774	0.1444	0.7218	0.9480	0.2119	1.107	1.109
	1.1549	0.2888	1.4437	0.9757	0.2247	1.208	1.207
	2.8848	0.7212	3.6060	1.0502	0.2648	1.532	1.541
	0.4909	0.2310	0.7219	0.9484	0.2112	1.104	1.106
	0.9813	0.4618	1.4431	0.9766	0.2231	1.200	1.199
	2.4512	1.1536	3.6048	1.0517	0.2606	1.510	1.521
						S.D. = 0.27%	

Molality (m) = g. moles salt/1000 g. H_2O. Ionic strength (I_T) = $m_{\text{NaCl}} + m_{\text{KCl}}$. Density = g./cc. ν = Kinematic viscosity, centistokes. $\eta_R = \eta_{\text{soln}} / \eta_{H_2O}$.

Table III. Relative Viscosities and Densities of Ternary Aqueous NaCl–Na_2SO_4 Solutions

Temp., °C.	Molality		Ionic Strength NaCl + Na_2SO_4	Density	ν, Cs.	η_R	
	NaCl	Na_2SO_4				Exptl.	Calcd.
25	0.6716	0.0118	0.7069	1.0250	0.9258	1.066	1.068
	1.3431	0.0235	1.4138	1.0515	0.9657	1.141	1.143
	3.3578	0.0589	3.5344	1.1230	1.1426	1.441	1.442
	0.6362	0.0236	0.7069	1.0252	0.9276	1.068	1.070
	1.2724	0.0471	1.4138	1.0516	0.9688	1.144	1.147
	3.1810	0.1178	3.5344	1.1234	1.1501	1.451	1.453
	0.5514	0.0518	0.7068	1.0253	0.9313	1.073	1.075
	1.1028	0.1036	1.4137	1.0520	0.9761	1.153	1.154
	2.7569	0.2591	3.5343	1.1239	1.1688	1.476	1.480
40	0.6716	0.0118	0.7069	1.0196	0.6889	1.076	1.076
	1.3431	0.0235	1.4138	1.0455	0.7228	1.158	1.157
	3.3578	0.0589	3.5344	1.1157	0.8566	1.464	1.465
	0.6362	0.0236	0.7069	1.0197	0.6898	1.078	1.078
	1.2724	0.0471	1.4138	1.0456	0.7247	1.161	1.160
	3.1810	0.1178	3.5344	1.1161	0.8608	1.472	1.474
	0.5514	0.0518	0.7068	1.0198	0.6922	1.081	1.082
	1.1028	0.1036	1.4137	1.0459	0.7288	1.168	1.166
	2.7569	0.2591	3.5343	1.1167	0.8717	1.491	1.496
60	0.6716	0.0118	0.7069	1.0102	0.5012	1.085	1.085
	1.3431	0.0235	1.4138	1.0356	0.5285	1.173	1.172
	3.3578	0.0589	3.5344	1.1050	0.6277	1.487	1.489
	0.6362	0.0236	0.7069	1.0103	0.5016	1.086	1.086
	1.2724	0.0471	1.4138	1.0358	0.5295	1.176	1.175
	3.1810	0.1178	3.5344	1.1054	0.6299	1.493	1.497
	0.5514	0.0518	0.7068	1.0104	0.5029	1.089	1.090
	1.1028	0.1036	1.4137	1.0362	0.5318	1.181	1.178
	2.7569	0.2591	3.5343	1.1061	0.6357	1.507	1.514
75	0.6729	0.0118	0.7083	1.0022	0.4116	1.090	1.091
	1.3456	0.0236	1.4164	1.0276	0.4358	1.183	1.182
	3.3637	0.0590	3.5407	1.0970	0.5185	1.503	1.506
	0.6375	0.0236	0.7083	1.0022	0.4125	1.092	1.092
	1.2749	0.0472	1.4165	1.0277	0.4361	1.184	1.184
	3.1870	0.1180	3.5410	1.0974	0.5204	1.509	1.512
	0.5524	0.0519	0.7082	1.0023	0.4132	1.095	1.095
	1.1049	0.1038	1.4164	1.0280	0.4371	1.187	1.186
	2.7621	0.2596	3.5409	1.0980	0.5229	1.517	1.527

(*Continued*)

Table III. *Continued*

Temp., °C.	Molality		Ionic Strength NaCl + Na_2SO_4	Density	ν, Cs.	η_R	
	NaCl	Na_2SO_4				Exptl.	Calcd.
100	0.6748	0.0118	0.7103	0.9861	0.3140	1.098	1.099
	1.3494	0.0236	1.4204	1.0116	0.3335	1.196	1.196
	3.3726	0.0592	3.5500	1.0813	0.3981	1.527	1.530
	0.6395	0.0237	0.7105	0.9860	0.3144	1.099	1.100
	1.2785	0.0473	1.4206	1.0116	0.3337	1.197	1.197
	3.1960	0.1183	3.5510	1.0816	0.3989	1.530	1.535
	0.5540	0.0521	0.7103	0.9862	0.3151	1.102	1.102
	1.1080	0.1041	1.4204	1.0119	0.3342	1.199	1.198
	2.7698	0.2603	3.5508	1.0822	0.4000	1.535	1.545
125	0.6787	0.0119	0.7114	0.9677	0.2532	1.104	1.107
	1.3569	0.0238	1.4282	0.9937	0.2695	1.207	1.209
	3.3900	0.0594	3.5683	1.0645	0.3225	1.547	1.552
	0.6434	0.0238	0.7148	0.9676	0.2533	1.105	1.107
	1.2857	0.0476	1.4285	0.9937	0.2695	1.207	1.209
	3.2135	0.1190	3.5740	1.0649	0.3228	1.549	1.555
	0.5572	0.0524	0.7142	0.9678	0.2538	1.107	1.108
	1.1141	0.1047	1.4283	0.9939	0.2696	1.208	1.208
	2.7849	0.2618	3.5702	1.0654	0.3229	1.550	1.562
150	0.6857	0.0120	0.7218	0.9472	0.2133	1.113	1.114
	1.3704	0.0240	1.4424	0.9740	0.2271	1.219	1.220
	3.4219	0.0600	3.6020	1.0467	0.2727	1.572	1.575
	0.6504	0.0241	0.7227	0.9471	0.2130	1.111	1.114
	1.2989	0.0481	1.4432	0.9740	0.2271	1.219	1.220
	3.2457	0.1202	3.6062	1.0471	0.2721	1.570	1.578
	0.5628	0.0529	0.7215	0.9473	0.2135	1.114	1.114
	1.1253	0.1058	1.4426	0.9742	0.2272	1.219	1.218
	2.8126	0.2644	3.6057	1.0476	0.2719	1.569	1.581

S.D. = 0.27%

Molality (m) = g. moles salt/1000 g. H_2O. Ionic strength (I_T) = $m_{NaCl} + 3m_{Na_2SO_4}$. Density = g./cc. ν = kinematic viscosity, centistokes. $\eta_R = \eta_{soln}/\eta_{H_2O}$.

Table IV. Relative Viscosities and Densities of Ternary Aqueous NaCl—$MgSO_4$ Solutions

Temp., °C.	Molality		Ionic Strength NaCl + $MgSO_4$	Density	ν, Cs.	η_R	
	NaCl	$MgSO_4$				Exptl.	Calcd.
25	0.6370	0.0177	0.7078	1.0246	0.9290	1.069	1.070
	1.2740	0.0354	1.4156	1.0502	0.9714	1.146	1.149
	3.1852	0.0885	3.5390	1.1204	1.1543	1.453	1.425
	0.5662	0.0354	0.7078	1.0238	0.9343	1.074	1.076
	1.1325	0.0708	1.4156	1.0490	0.9812	1.156	1.159
	2.8312	0.1770	3.5390	1.1180	1.1746	1.475	1.475
	0.4813	0.0566	0.7078	1.0229	0.9401	1.080	1.083
	0.9626	0.1132	1.4156	1.0476	0.9921	1.167	1.171
	2.4065	0.2831	3.5390	1.1151	1.2012	1.504	1.506
40	0.6370	0.0177	0.7078	1.0191	0.6907	1.078	1.076
	1.2740	0.0354	1.4156	1.0442	0.7262	1.162	1.162
	3.1852	0.0885	3.5390	1.1133	0.8640	1.474	1.473
	0.5662	0.0354	0.7078	1.0184	0.6938	1.083	1.083
	1.1325	0.0708	1.4156	1.0430	0.7319	1.170	1.169
	2.8312	0.1770	3.5390	1.1110	0.8766	1.492	1.492
	0.4813	0.0566	0.7078	1.0175	0.6972	1.087	1.088
	0.9626	0.1132	1.4156	1.0417	0.7384	1.178	1.179
	2.4065	0.2831	3.5390	1.1082	0.8926	1.515	1.518
60	0.6370	0.0177	0.7078	1.0097	0.5020	1.086	1.082
	1.2740	0.0354	1.4156	1.0344	0.5304	1.176	1.175
	3.1852	0.0885	3.5390	1.1027	0.6320	1.494	1.496
	0.5662	0.0354	0.7078	1.0092	0.5036	1.090	1.090
	1.1325	0.0708	1.4156	1.0334	0.5336	1.182	1.180
	2.8312	0.1770	3.5390	1.1006	0.6391	1.508	1.511
	0.4813	0.0566	0.7078	1.0084	0.5054	1.093	1.094
	0.9626	0.1132	1.4156	1.0321	0.5369	1.188	1.186
	2.4065	0.2831	3.5390	1.0980	0.6483	1.526	1.531
75	0.6382	0.0177	0.7091	1.0015	0.4130	1.093	1.093
	1.2765	0.0355	1.4184	1.0266	0.4375	1.187	1.184
	3.1910	0.0886	3.5455	1.0946	0.5216	1.509	1.512
	0.5673	0.0355	0.7092	1.0009	0.4138	1.095	1.095
	1.1347	0.0709	1.4184	1.0257	0.4391	1.190	1.188
	2.8365	0.1773	3.5456	1.0925	0.5265	1.520	1.524
	0.4822	0.0567	0.7091	1.0002	0.4147	1.096	1.098
	0.9645	0.1135	1.4184	1.0245	0.4415	1.195	1.192
	2.4110	0.2836	3.5456	1.0898	0.5326	1.534	1.541
100	0.6400	0.0178	0.7111	0.9854	0.3147	1.100	1.100
	1.2802	0.0356	1.4225	1.0109	0.3344	1.199	1.197
	3.1997	0.0889	3.5552	1.0790	0.4000	1.531	1.535
	0.5690	0.0356	0.7112	0.9849	0.3151	1.101	1.102
	1.1380	0.0711	1.4224	1.0098	0.3352	1.200	1.198
	2.8443	0.1778	3.5554	1.0770	0.4024	1.537	1.543
	0.4836	0.0569	0.7111	0.9841	0.3155	1.101	1.104
	0.9673	0.1138	1.4225	1.0086	0.3363	1.203	1.199
	2.4177	0.2844	3.5554	1.0743	0.4056	1.545	1.555
125	0.6435	0.0179	0.7150	0.9670	0.2533	1.104	1.107
	1.2875	0.0358	1.4306	0.9929	0.2699	1.208	1.208
	3.2170	0.0893	3.5743	1.0621	0.3233	1.547	1.556
	0.5722	0.0358	0.7152	0.9665	0.2535	1.104	1.108
	1.1444	0.0715	1.4305	0.9918	0.2702	1.208	1.207
	2.8598	0.1787	3.5748	1.0602	0.3244	1.550	1.562
	0.4862	0.0572	0.7150	0.9656	0.2537	1.104	1.108
	0.9728	0.1144	1.4306	0.9906	0.2706	1.208	1.206
	2.4308	0.2860	3.5747	1.0574	0.3259	1.553	1.569
150	0.6499	0.0180	0.7221	0.9464	0.2129	1.110	1.113
	1.3009	0.0361	1.4454	0.9732	0.2271	1.218	1.218
	3.2484	0.0902	3.6093	1.0445	0.2724	1.568	1.578
	0.5781	0.0361	0.7226	0.9459	0.2130	1.110	1.113
	1.1559	0.0722	1.4449	0.9720	0.2272	1.217	1.216
	2.8881	0.1805	3.6102	1.0423	0.2729	1.567	1.582
	0.4911	0.0578	0.7222	0.9450	0.2129	1.109	1.113
	0.9828	0.1156	1.4453	0.9705	0.2271	1.214	1.213
	2.4548	0.2888	3.6100	1.0395	0.2732	1.565	1.587

S.D. = 0.38%

Molality (m) = g. moles salt/1000 g. H_2O. Ionic strength (I_T) = $m_{NaCl} + 4m_{MgSO_4}$. Density = g./cc. ν = kinematic viscosity, centistokes. $\eta_R = \eta_{soln}/\eta_{H_2O}$.

were calculated from literature data (*2, 5, 12, 15*). The ionic strength fractions of NaCl, $MgCl_2$, and KCl were calculated using Equation 6 and

$$X_{MgSO_4} = 1 - X_{NaCl} - X_{MgCl_2} - X_{KCl}$$

The Othmer constants of the mixture were calculated from:

$$A_M = \Sigma A_{0i} \cdot X_i \qquad (8)$$

$$B_M = \Sigma B_{0i} \cdot X_i \qquad (9)$$

and the viscosity was determined from Equation 1.

Thus the relative viscosity of the calcium-free sea water was calculated with the equation

$$\log \eta_R = 0.04280I + 0.00123I^2 + 0.000131I^3 + (-0.03724I + 0.01859I^2 - 0.00271I^3) \log \eta_w \qquad (10a)$$

for standard calcium-free sea water ($I = 0.70989$)

$$\log \eta_R = 0.03103 - 0.01803 \log \eta_w \qquad (10b)$$

and for the absolute viscosity of calcium-free standard sea water

$$\log \eta_{s.w.} = 0.03103 + 0.98197 \log \eta_w \qquad (10c)$$

The experimental and calculated data are compared in Table VI. The concentration factor used in this table is the salt content per 1000 grams of water in the given solution divided by the salt content per 1000 grams of water in standard sea water. The slight increase of concentration factors with temperature was caused by water evaporation inside of the viscometer. The standard deviation of the experimental and calculated viscosities is 0.28% up to a concentration factor of 2, 0.45% up to a concentration factor of 2.5, and 0.63% up to a concentration factor of 3.

Table V. Composition of Sea Water

Ionic Composition	P.p.m.	Component	Salt Composition: Carbonate-free sea water molality	Calcium-free sea water molality	Regrouped composition molality
Sodium	10,561	NaCl	0.41674	0.41674	0.47716
Magnesium	1,272	Na_2SO_4	0.02979	0.02979	...
Calcium	400	$MgCl_2$	0.05423	0.06457	0.03478
		$MgSO_4$	...	...	0.02979
Potassium	480	$CaCl_2$	0.01034	...	...
Chloride	18,980	KCl	0.00923	0.00923	0.00923
Sulfate	2,649	KBr	0.00084	0.00084	...
Bicarbonate	142				
Bromide	65				
Total ionic strength (I_T)			0.70989	0.70989	0.70989

Table VII. Relative Viscosity of Sea Water at 25° C.

	Salinity 5	10	20	30	40
Krümmel (*8*)	1.010	1.022	1.044	1.069	1.093
Calculated	1.010	1.021	1.043	1.066	1.090
	Chlorinity 5	**10**	**15**	**20**	
Miyake (*10*)	1.026	1.041	1.059	1.079	
Calculated	1.019	1.039	1.059	1.081	

Table VIII. Relative Viscosity of Sea Water

Chlorinity[a]	25° C.	50° C.	75° C.	100° C.	125° C.	150° C.	Salinity[b]
5.0	1.019	1.022	1.024	1.026	1.028	1.029	9.05
10.0	1.039	1.044	1.049	1.052	1.055	1.057	18.11
15.0	1.059	1.067	1.073	1.078	1.082	1.085	27.16
20.0	1.081	1.090	1.098	1.104	1.109	1.113	36.21
25.0	1.103	1.114	1.123	1.130	1.136	1.140	45.27
30.0	1.127	1.139	1.149	1.156	1.162	1.167	54.32
35.0	1.152	1.165	1.175	1.183	1.189	1.195	63.37
40.0	1.178	1.191	1.202	1.210	1.216	1.222	72.43
45.0	1.206	1.219	1.229	1.238	1.244	1.250	81.48
50.0	1.235	1.248	1.259	1.267	1.273	1.279	90.53
55.0	1.266	1.279	1.289	1.297	1.304	1.309	99.60
60.0	1.300	1.312	1.322	1.330	1.336	1.341	108.66

[a] Grams chlorine and bromine (expressed as equivalent chlorine) in kg. sea water. [b] Grams salt per kg. sea water.

Table VI. Relative Viscosities and Densities of Calcium-Free Synthetic Sea Waters

Temp., ° C.	Concn. Factor	Total Ionic Strength	Density	ν, Cs.	η_R Exptl.	η_R Calcd.
25	1.0	0.7099	1.0227	0.9367	1.076	1.076
	1.5	1.0648	1.0350	0.9600	1.116	1.117
	2.0	1.4198	1.0470	0.9851	1.159	1.161
	2.5	1.7747	1.0590	1.0120	1.204	1.207
	3.0	2.1297	1.0704	1.0416	1.252	1.256
40	1.0	0.7099	1.0174	0.6954	1.084	1.082
	1.5	1.0648	1.0294	0.7144	1.127	1.125
	2.0	1.4198	1.0411	0.7343	1.171	1.169
	2.5	1.7747	1.0529	0.7556	1.219	1.216
	3.0	2.1297	1.0641	0.7782	1.269	1.265
60	1.0	0.7099	1.0081	0.5046	1.090	1.089
	1.5	1.0648	1.0201	0.5194	1.136	1.133
	2.0	1.4198	1.0317	0.5348	1.183	1.179
	2.5	1.7747	1.0433	0.5509	1.232	1.225
	3.0	2.1297	1.0543	0.5677	1.283	1.274
75	1.0019	0.7113	1.0001	0.4145	1.096	1.093
	1.5029	1.0669	1.0119	0.4268	1.141	1.139
	2.0039	1.4225	1.0234	0.4401	1.190	1.185
	2.5048	1.7782	1.0352	0.4535	1.241	1.231
	3.0058	2.1338	1.0460	0.4675	1.292	1.280
100	1.0048	0.7133	0.9834	0.3151	1.099	1.099
	1.5072	1.0699	0.9954	0.3252	1.148	1.145
	2.0096	1.4266	1.0071	0.3357	1.199	1.193
	2.5120	1.7832	1.0186	0.3462	1.250	1.240
	3.0144	2.1399	1.0299	0.3572	1.305	1.289
125	1.0104	0.7173	0.9652	0.2535	1.103	1.105
	1.5156	1.0759	0.9776	0.2618	1.153	1.153
	2.0208	1.4345	0.9897	0.2704	1.206	1.201
	2.5260	1.7932	1.0016	0.2789	1.259	1.248
	3.0312	2.1518	1.0132	0.2880	1.315	1.297
150	1.0207	0.7246	0.9445	0.2130	1.108	1.110
	1.5310	1.0869	0.9575	0.2200	1.160	1.160
	2.0414	1.4492	0.9702	0.2274	1.215	1.208
	2.5518	1.8115	0.9826	0.2346	1.270	1.256
	3.0621	2.1738	0.9948	0.2421	1.327	1.306

S.D. = 0.63%

Density = g./cc. ν = kinematic viscosity, centistokes. $\eta_R = \eta_{soln} / \eta_{H_2O}$.

LITERATURE DATA

The experimental technique developed to calculate viscosities of ternary mixtures was used to check the only other available data on ternary systems. Ruby and Kawai (*13*) measured viscosities in the ternary NaCl-KCl-H_2O system at 25° C., and Ezrokhi (*3*) published data on this system at 25°, 40°, and 60° C. The data given by Ruby and Kawai were correlated with an average deviation of ±0.19% and those of Ezrokhi with an average deviation of ±0.55% up to an ionic strength of 3.0.

Unfortunately, available data on sea water viscosity cover only a narrow temperature and concentration range. Dorsey (*1*) summarized Krümmel's (*8*) data over the 0° to 30° C. temperature range for salinities from 5 to 40, and Myake and Koizumi (*10*) gave new results over the same temperature and concentration range. Their data are compared with the calculated results for the synthetic sea water in Table VII. The average deviation between the given and calculated data is ±0.21%.

CONCLUSIONS

Since all other data on the viscosity of sea water and its concentrates are estimated data, based on sodium chloride solutions of equivalent chloride content or on some other assumption, it is felt that the present measurements on calcium-free sea water represent the best available information, and Equations 10 can be used for the calculation of sea water viscosities. Deviations between calculated viscosities of the calcium-free sea water and calcium-containing sea water were within the precision of the method. Table VIII gives the interpolated data on sea water and its concentrates as a function of chlorinity and salinity.

Additional tables on salt and sea water solutions containing density, vapor pressure, and viscosity data were prepared for the Office of Saline water (*4*).

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Thermal Properties of Propane

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This contribution summarizes the results of an experimental investigation of the thermal properties of propane as part of a continuing effort to determine such properties for materials that are gases under normal conditions, light hydrocarbons, and their mixtures. New data on the isobaric heat capacity are presented. These data are compared with previously published experimental data in regions where such comparisons are possible. Published data on propane, including *PVT* determinations, isobaric heat capacity, latent heat, isothermal throttling coefficient, and Joule-Thomson data, were used together with the new data to determine values of enthalpy in the liquid, critical, super-critical, gaseous, and two-phase regions in the temperature range from −280° to +300° F., at pressures up to 2000 p.s.i.a. These results were checked for thermodynamic consistency and are believed to be accurate to better than 0.5%. The BWR equation of state was used, together with published data on isothermal enthalpy departures, to extend the upper limit of the tabulation of thermal properties to +500° F. A table of enthalpy values is presented.

TABLES and charts of thermodynamic properties of propane have been published (*2, 3, 4, 6, 18, 28, 32, 34, 38*). The ranges in temperature and pressure covered by these published tables are indicated in Figure 1. The values of the thermal properties, enthalpy and entropy, presented in these tables were calculated using heat capacity data at low pressure and volumetric (*PVT*) data. This general procedure has been followed as there are few calorimetric data for propane at elevated pressures, with the exception of data on the latent heat of vaporization (*6, 13, 30*) and results of Joule-Thomson experiments (*31*).

Recently, results of direct experimental determinations of the effect of both pressure and temperature on the thermal properties of propane have been published (*9, 12, 35, 37*). These data extend over a considerable range of temperatures (−250° to +400° F.) at pressures up to 2000 p.s.i.a. However, information was sketchy in the regions near the critical point and in the vicinity of the two-phase region—i.e., where rapid changes in properties are encountered. Therefore, the purposes of this contribution are to present the results of experimental determinations in these regions and to summarize all published experimental data on the