Viscosities of Aqueous Solutions of $Fe_2(SO_4)_3$ Containing $NaNO_3$, KNO_3, NaBr, or KBr from 293.1 to 323.1 K

Francisco Chenlo,* Ramón Moreira, Gerardo Pereira, and María J. Vázquez

Department of Chemical Engineering, University of Santiago de Compostela, 15706 Santiago, Spain

We report the kinematic viscosities of aqueous solutions of ferric sulfate containing sodium nitrate, potassium nitrate, sodium bromide, or potassium bromide at concentrations of up to 1 mol·L^{-1} (or up to the solubility limit) and at temperatures ranging from 293.1 to 323.1 K. Concentrations of $NaNO_3$ or NaBr altered the viscosities of the unsupplemented $Fe_2(SO_4)_3$ solutions by no more than 3%. For each concentration of $Fe_2(SO_4)_3$ employed, the measured viscosities of solutions with KNO_3 or KBr were fitted to within 0.9% by semiempirical equations. For each solution studied, its density at 298.1 K is also reported.

Introduction

A common means of removing H_2S from gaseous industrial effluent is to promote its absorption by liquid media in which it undergoes a redox reaction. The absorbents most favored in recent years have been ferric sulfate solutions (Asai et al., 1990), which can be regenerated biotechnologically (Jensen and Webb, 1995). The main factors governing the complex mechanism of the absorption process are the pH of the medium, which can be controlled by addition of acids or bases, and ionic strength, which can be controlled by addition of inert salts (Asai et al., 1990; Pagella et al., 1996).

Application of theoretical models of gas absorption (Danckwerts, 1970) requires knowledge of physical properties of the system. In particular, the viscosity and density of the liquid-phase affect the solubility and diffusivity of the gas in the liquid. With the absorption of H_2S by $Fe_2(SO_4)_3$ solutions in mind, in previous work (Chenlo et al., 1997a,b) we set about remedying the lack of systematic tables of the viscosities of aqueous $Fe_2(SO_4)_3$ solutions in the presence of other electrolytes; specifically, we determined the kinematic viscosities of aqueous $Fe_2(SO_4)_3$ solutions whose pH and ionic strength had been modified by addition of various concentrations of sodium sulfate, sodium chloride, potassium sulfate, and potassium chloride. It was found that kinematic viscosity increased upon addition of some salts but decreased upon addition of others, allowing great freedom for simultaneous control of pH, ionic strength, and viscosity. However, it allowed control of pH and/or ionic strength without affecting viscosity significantly. We report the influence of $NaNO_3$, KNO_3, NaBr, and KBr on the viscosity of $Fe_2(SO_4)_3$ solutions.

Experimental Section

$Fe_2(SO_4)_3$, $NaNO_3$, KNO_3, NaBr, and KBr were supplied by Merck; all were dried to constant mass before use, and all were supplied with a purity exceeding 99.5% except $Fe_2(SO_4)_3$, which contained water of crystallization and whose purity after drying was determined spectrophotometrically as 84%. Solutions in degassed distilled water

* To whom correspondence should be addressed. E-mail: eqchenlo@uscmail.usc.es.

Table 1. Kinematic Viscosities ν (10^6 m^2·s^{-1}) of the Ternary Systems with 0.125 mol·L^{-1} $Fe_2(SO_4)_3$ at Various Temperatures, with Densities at 298.1 K

$Fe_2(SO_4)_3$ (A) + KNO_3 (B) + H_2O (C)

T/K	w_A = 0.047 33, w_B = 0.024 18	w_A = 0.046 71, w_B = 0.047 72	w_A = 0.046 04, w_B = 0.070 54	w_A = 0.045 41, w_B = 0.092 78
293.1	1.127	1.106	1.093	1.079
298.1	1.009	0.997	0.981	0.966
303.1	0.902	0.888	0.876	0.861
308.1	0.815	0.803	0.797	0.781
313.1	0.740	0.731	0.725	0.710
318.1	0.669	0.670	0.666	0.655
323.1	0.617	0.618	0.614	0.604
ρ	1056.2	1070.3	1085.9	1100.9

$Fe_2(SO_4)_3$ (A) + $NaNO_3$ (B) + H_2O (C)

T/K	w_A = 0.047 34, w_B = 0.020 22	w_A = 0.046 78, w_B = 0.039 97	w_A = 0.046 17, w_B = 0.059 18	w_A = 0.045 67, w_B = 0.078 03
293.1	1.152	1.150	1.154	1.163
298.1	1.022	1.025	1.031	1.039
303.1	0.910	0.918	0.929	0.937
308.1	0.821	0.829	0.835	0.847
313.1	0.746	0.753	0.759	0.769
318.1	0.678	0.689	0.696	0.703
323.1	0.622	0.633	0.640	0.647
ρ	1055.8	1068.6	1082.6	1094.9

$Fe_2(SO_4)_3$ (A) + KBr (B) + H_2O (C)

T/K	w_A = 0.047 09, w_B = 0.028 18	w_A = 0.046 11, w_B = 0.055 18	w_A = 0.045 30, w_B = 0.081 30	w_A = 0.044 49, w_B = 0.106 46
293.1	1.112	1.082	1.057	1.031
298.1	0.995	0.970	0.948	0.929
303.1	0.889	0.870	0.853	0.837
308.1	0.800	0.787	0.772	0.762
313.1	0.729	0.717	0.705	0.694
318.1	0.660	0.654	0.647	0.640
323.1	0.608	0.605	0.597	0.591
ρ	1061.6	1084.0	1103.4	1123.6

$Fe_2(SO_4)_3$ (A) + NaBr (B) + H_2O (C)

T/K	w_A = 0.047 19, w_B = 0.024 41	w_A = 0.046 27, w_B = 0.047 86	w_A = 0.045 51, w_B = 0.070 61	w_A = 0.044 77, w_B = 0.092 63
293.1	1.144	1.141	1.139	1.133
298.1	1.017	1.018	1.018	1.011
303.1	0.909	0.911	0.913	0.914
308.1	0.822	0.821	0.826	0.829
313.1	0.745	0.749	0.748	0.752
318.1	0.675	0.681	0.686	0.689
323.1	0.617	0.626	0.630	0.635
ρ	1059.3	1080.4	1098.6	1117.1

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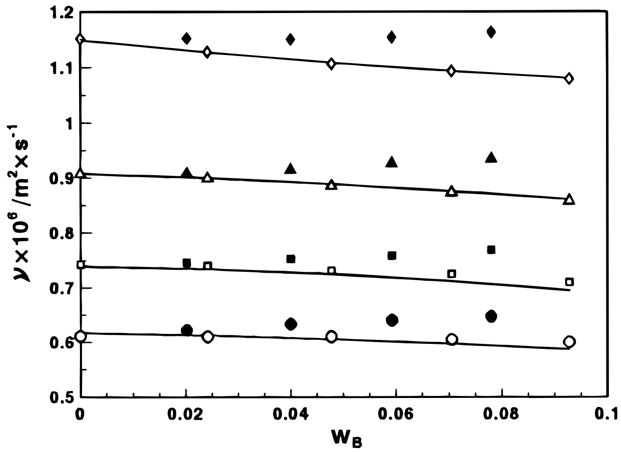

Figure 1. Kinematic viscosities of the ternary systems with 0.125 mol·L^{-1} $Fe_2(SO_4)_3$ at various concentrations of KNO_3 or $NaNO_3$ and temperatures. KNO_3: 293.1 K (◇), 303.1 K (△), 313.1 K (□), 323.1 K (○); lines were calculated with eq 3. $NaNO_3$: 293.1 K (◆), 303.1 K (▲), 313.1 K (■), 323.1 K (●).

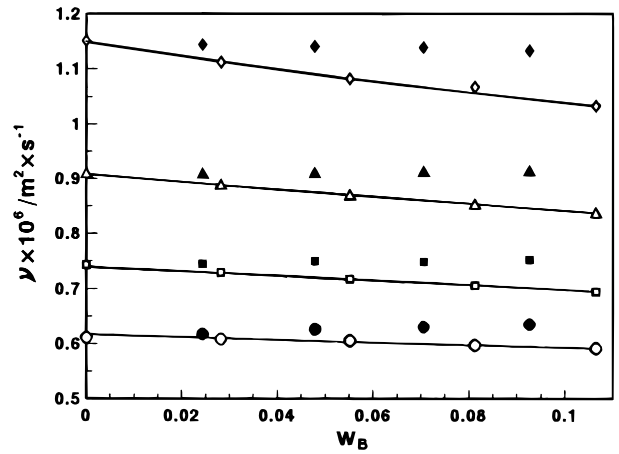

Figure 2. Kinematic viscosities of the ternary systems with 0.125 mol·L^{-1} $Fe_2(SO_4)_3$ at various concentrations of KBr or NaBr and temperatures. KBr: 293.1 K (◇), 303.1 K (△), 313.1 K (□), 323.1 K (○); lines were calculated with eq 3. NaBr: 293.1 K (◆), 303.1 K (▲), 313.1 K (■), 323.1 K (●).

Table 2. Kinematic Viscosities ν (10^6 m^2·s^{-1}) of the Ternary Systems with 0.250 mol·L^{-1} $Fe_2(SO_4)_3$ at Various Temperatures, with Densities at 298.1 K

$Fe_2(SO_4)_3$ (A) + KNO_3 (B) + H_2O (C)

T/K	w_A = 0.091 20 w_B = 0.023 30	w_A = 0.089 90 w_B = 0.045 92	w_A = 0.088 69 w_B = 0.067 95	w_A = 0.087 43 w_B = 0.089 32
293.1	1.305	1.274	1.252	1.233
298.1	1.152	1.128	1.112	1.098
303.1	1.021	1.005	0.993	0.983
308.1	0.915	0.905	0.893	0.888
313.1	0.826	0.818	0.814	0.807
318.1	0.754	0.748	0.742	0.740
323.1	0.695	0.690	0.683	0.678
ρ	1096.3	1112.1	1127.3	1143.5

$Fe_2(SO_4)_3$ (A) + $NaNO_3$ (B) + H_2O (C)

T/K	w_A = 0.091 27 w_B = 0.019 50	w_A = 0.090 20 w_B = 0.038 54	w_A = 0.089 06 w_B = 0.057 07	w_A = 0.088 06 w_B = 0.075 24
293.1	1.343	1.350	1.357	1.362
298.1	1.188	1.191	1.199	1.208
303.1	1.056	1.061	1.066	1.075
308.1	0.945	0.952	0.958	0.969
313.1	0.851	0.857	0.868	0.876
318.1	0.774	0.782	0.791	0.802
323.1	0.705	0.714	0.720	0.734
ρ	1095.1	1108.3	1122.3	1135.3

$Fe_2(SO_4)_3$ (A) + KBr (B) + H_2O (C)

T/K	w_A = 0.090 67 w_B = 0.027 13	w_A = 0.088 95 w_B = 0.053 21	w_A = 0.087 52 w_B = 0.078 53
293.1	1.304	1.269	1.238
298.1	1.156	1.128	1.103
303.1	1.026	1.004	0.989
308.1	0.922	0.907	0.890
313.1	0.833	0.821	0.809
318.1	0.759	0.750	0.739
323.1	0.694	0.687	0.678
ρ	1102.6	1124.0	1146.4

$Fe_2(SO_4)_3$ (A) + NaBr (B) + H_2O (C)

T/K	w_A = 0.090 78 w_B = 0.023 48	w_A = 0.089 23 w_B = 0.046 15	w_A = 0.087 75 w_B = 0.068 09	w_A = 0.086 39 w_B = 0.089 36
293.1	1.339	1.340	1.341	1.336
298.1	1.181	1.187	1.184	1.179
303.1	1.048	1.051	1.057	1.057
308.1	0.940	0.945	0.947	0.952
313.1	0.848	0.852	0.854	0.860
318.1	0.772	0.776	0.780	0.785
323.1	0.705	0.710	0.714	0.718
ρ	1101.3	1120.4	1139.3	1158.3

Table 3. Kinematic Viscosities ν (10^6 m^2·s^{-1}) of the Ternary Systems with 0.375 mol·L^{-1} $Fe_2(SO_4)_3$ at Various Temperatures with Densities at 298.1 K

$Fe_2(SO_4)_3$ (A) + KNO_3 (B) + H_2O (C)

T/K	w_A = 0.131 72 w_B = 0.022 43	w_A = 0.130 13 w_B = 0.044 32	w_A = 0.128 46 w_B = 0.065 62	w_A = 0.126 83 w_B = 0.086 38
293.1	1.541	1.514	1.491	1.489
298.1	1.360	1.326	1.304	1.308
303.1	1.196	1.173	1.164	1.157
308.1	1.071	1.051	1.041	1.036
313.1	0.965	0.949	0.941	0.937
318.1	0.873	0.859	0.848	0.851
323.1	0.790	0.781	0.778	0.777
ρ	1138.4	1152.4	1167.3	1182.4

$Fe_2(SO_4)_3$ (A) + $NaNO_3$ (B) + H_2O (C)

T/K	w_A = 0.131 88 w_B = 0.018 78	w_A = 0.130 33 w_B = 0.037 12	w_A = 0.128 90 w_B = 0.055 07	w_A = 0.127 23 w_B = 0.072 48
293.1	1.589	1.591	1.601	1.614
298.1	1.384	1.395	1.399	1.413
303.1	1.225	1.231	1.239	1.252
308.1	1.089	1.102	1.115	1.125
313.1	0.986	0.992	0.998	1.012
318.1	0.892	0.901	0.907	0.918
323.1	0.806	0.818	0.829	0.839
ρ	1137.1	1150.6	1163.8	1177.4

$Fe_2(SO_4)_3$ (A) + KBr (B) + H_2O (C)

T/K	w_A = 0.131 14 w_B = 0.026 15	w_A = 0.129 85 w_B = 0.038 84	w_A = 0.129 01 w_B = 0.051 45
293.1	1.541	1.499	1.484
298.1	1.346	1.316	1.305
303.1	1.189	1.171	1.155
308.1	1.058	1.043	1.033
313.1	0.952	0.941	0.933
318.1	0.862	0.853	0.847
323.1	0.786	0.780	0.775
ρ	1143.5	1153.1	1162.5

$Fe_2(SO_4)_3$ (A) + NaBr (B) + H_2O (C)

T/K	w_A = 0.131 28 w_B = 0.022 64	w_A = 0.129 35 w_B = 0.044 61	w_A = 0.127 13 w_B = 0.065 75	w_A = 0.125 04 w_B = 0.086 23
293.1	1.574	1.577	1.580	1.590
298.1	1.374	1.378	1.384	1.394
303.1	1.212	1.221	1.228	1.237
308.1	1.087	1.093	1.100	1.107
313.1	0.973	0.982	0.989	0.998
318.1	0.882	0.888	0.896	0.903
323.1	0.804	0.811	0.817	0.825
ρ	1142.3	1159.3	1179.6	1199.9

Table 4. Kinematic Viscosities ν (10^6 $m^2 \cdot s^{-1}$) of the Ternary Systems with 0.500 mol·L^{-1} $Fe_2(SO_4)_3$ at Various Temperatures, with Densities at 298.1 K

$Fe_2(SO_4)_3$ (A) + KNO_3 (B) + H_2O (C)

T/K	w_A = 0.169 40 w_B = 0.021 64	w_A = 0.167 47 w_B = 0.042 78	w_A = 0.165 16 w_B = 0.063 28	w_A = 0.163 40 w_B = 0.083 47
293.1	1.856	1.817	1.779	1.759
298.1	1.616	1.589	1.560	1.541
303.1	1.417	1.388	1.368	1.360
308.1	1.253	1.233	1.220	1.217
313.1	1.123	1.106	1.095	1.095
318.1	1.013	1.000	0.989	0.990
323.1	0.917	0.910	0.906	0.904
ρ	1179.3	1193.9	1209.6	1223.6

$Fe_2(SO_4)_3$ (A) + $NaNO_3$ (B) + H_2O (C)

T/K	w_A = 0.169 98 w_B = 0.018 15	w_A = 0.168 10 w_B = 0.035 91	w_A = 0.166 03 w_B = 0.053 20	w_A = 0.164 07 w_B = 0.070 10
293.1	1.900	1.928	1.946	1.975
298.1	1.650	1.669	1.693	1.716
303.1	1.442	1.463	1.482	1.512
308.1	1.273	1.296	1.315	1.337
313.1	1.135	1.157	1.177	1.203
318.1	1.025	1.043	1.063	1.083
323.1	0.926	0.946	0.965	0.983
ρ	1176.6	1190.5	1204.3	1218.6

$Fe_2(SO_4)_3$ (A) + KBr (B) + H_2O (C)

T/K	w_A = 0.169 02 w_B = 0.025 28	w_A = 0.167 37 w_B = 0.037 56	w_A = 0.166 26 w_B = 0.049 73
293.1	1.827	1.799	1.786
298.1	1.590	1.575	1.558
303.1	1.396	1.386	1.367
308.1	1.238	1.229	1.220
313.1	1.106	1.098	1.091
318.1	1.000	0.996	0.990
323.1	0.907	0.902	0.898
ρ	1183.0	1192.9	1202.6

$Fe_2(SO_4)_3$ (A) + NaBr (B) + H_2O (C)

T/K	w_A = 0.169 10 w_B = 0.021 87	w_A = 0.166 32 w_B = 0.043 01	w_A = 0.163 81 w_B = 0.063 55	w_A = 0.161 30 w_B = 0.083 43
293.1	1.907	1.897	1.910	1.941
298.1	1.652	1.652	1.667	1.692
303.1	1.450	1.446	1.462	1.485
308.1	1.277	1.281	1.293	1.315
313.1	1.150	1.147	1.160	1.178
318.1	1.034	1.035	1.044	1.056
323.1	0.936	0.939	0.948	0.962
ρ	1182.4	1202.2	1220.6	1239.6

were made up with nominal $Fe_2(SO_4)_3$ concentrations of 0.125, 0.250, 0.375, and 0.500 mol·L^{-1} and nominal concentrations of $NaNO_3$, KNO_3, NaBr, or KBr ranging from 0.25 mol·L^{-1} to 1.00 mol·L^{-1} or to the limit of the solubility of these salts in the $Fe_2(SO_4)_3$ solution, if lower than 1.00 mol·L^{-1}; solutions were made up by mass using a Mettler AJ 150 balance with a precision of ±0.0001 g and were subsequently filtered. Concentrations are quoted in tables as mass fractions; none deviated from the nominal value by as much as ±0.1%.

The kinematic viscosities were determined in a Schott-Geräte AVS 350 automatic Ubbelohde viscosimeter at temperatures ranging from 293.1 K to 323.1 K at 5 K intervals as described elsewhere (Chenlo et al., 1996, 1997c). All measurements were quintuplicated, and values deviating by more than 0.2% from the mean were discarded. The densities of the solutions at 298.1 K were measured in a Bosch S2000/30 densitometric balance with a precision of ±0.0001 g·cm^{-3} (maximum deviations from nominal values were less than 0.02%). The precision of

Table 5. Parameters C_B and D_B of Eq 3 for the Dependence of the Kinematic Viscosity of the Listed ($Fe_2(SO_4)_3$ + KNO_3) Systems on KNO_3 Concentration at Various Temperatures

T/K	C_B/(g of solution· g of solute^{-1})	D_B/(g of solution· g of solute^{-1})^2
$Fe_2(SO_4)_3$ 0.125 M (A) + KNO_3 (B) + H_2O (C)		
293.1	−0.8460	1.9439
298.1	−0.2683	−3.1222
303.1	−0.2614	−3.3373
308.1	−0.0445	−4.5525
313.1	−0.1153	−5.8272
318.1	−0.0189	−3.1618
323.1	−0.2586	−3.1029
$Fe_2(SO_4)_3$ 0.250 M (A) + KNO_3 (B) + H_2O (C)		
293.1	−2.2311	11.7112
298.1	−2.0359	11.1841
303.1	−1.9815	11.8662
308.1	−1.8353	11.4884
313.1	−1.6864	11.1869
318.1	−1.4535	9.7860
323.1	−0.9651	4.7919
$Fe_2(SO_4)_3$ 0.375 M (A) + KNO_3 (B) + H_2O (C)		
293.1	−2.7084	19.0454
298.1	−2.4900	16.9688
303.1	−2.3636	16.4314
308.1	−2.0735	13.8794
313.1	−1.8169	12.1212
318.1	−1.8047	12.5713
323.1	−1.8229	13.8251
$Fe_2(SO_4)_3$ 0.500 M (A) + KNO_3 (B) + H_2O (C)		
293.1	−1.6000	6.7036
298.1	−1.4245	5.8585
303.1	−1.6361	9.1404
308.1	−1.6511	10.9411
313.1	−1.5004	10.1987
318.1	−1.3368	8.9445
323.1	−1.2081	8.8807

the temperature control in all measurements was ±0.05 K.

Results

Tables 1−4 list the measured kinematic viscosity of each solution at each temperature, together with its density at 298.1 K. The viscosities of aqueous $Fe_2(SO_4)_3$ solutions in the absence of other salts have been published previously (Chenlo et al., 1997a). Figures 1 and 2 show experimental values of viscosity at various concentrations of sodium and potassium salts and temperatures of some systems studied (as examples).

Both the sodium salts were found to have minimal influence on the viscosity of $Fe_2(SO_4)_3$ solutions. In both cases, the measured viscosities of the $Fe_2(SO_4)_3$ + water + sodium salt system were within 3%, or 0.025 × 10^{-6} $m^2 \cdot s^{-1}$, of ν_0, the viscosity of the system with no second salt as calculated from the equation (Chenlo et al., 1997a)

$$\nu_0/(m^2 \cdot s^{-1}) = \nu_w/(m^2 \cdot s^{-1}) + 4.1466 \times 10^{-7}\, w_0^{1.49}\, (8.5878 \times 10^7)/(T/K)^3 \quad (1)$$

where ν_w is the kinematic viscosity of water at temperature T and w_0 is the mass fraction of $Fe_2(SO_4)_3$ in an $Fe_2(SO_4)_3$ + water system in which $Fe_2(SO_4)_3$ has the same molar concentration as in the $Fe_2(SO_4)_3$ + water + second salt system in question; w_0 is given as a function of M, the molarity of the unsupplemented $Fe_2(SO_4)_3$ solution at 298.1 K, by

$$w_0 = \frac{400M}{997.07 + 340.34M} \quad (2)$$

Table 6. Parameters C_B and D_B of Eq 3 for the Dependence of the Kinematic Viscosity of the Listed ($Fe_2(SO_4)_3$ + KBr) Systems on KBr Concentration at Various Temperatures

T/K	C_B/(g of solution·g of solute^{-1})	D_B/(g of solution·g of solute^{-1})^2
	$Fe_2(SO_4)_3$ 0.125 M (A) + KBr (B) + H_2O (C)	
293.1	−1.1475	1.3326
298.1	−0.8223	−0.3010
303.1	−0.7528	−0.0807
308.1	−0.7107	0.5843
313.1	−0.4849	−1.0182
318.1	−0.6452	1.6790
323.1	−0.4095	0.0827
	$Fe_2(SO_4)_3$ 0.250 M (A) + KBr (B) + H_2O (C)	
293.1	−2.0866	9.8352
298.1	−1.7244	7.4155
303.1	−1.7577	9.6590
308.1	−1.4174	6.5352
313.1	−1.3144	6.7455
318.1	−1.0751	4.9380
323.1	−0.9800	4.6646
	$Fe_2(SO_4)_3$ 0.375 M (A) + KBr (B) + H_2O (C)	
293.1	−2.8729	18.4290
298.1	−2.9239	22.2923
303.1	−2.6572	19.2102
308.1	−2.7404	22.9827
313.1	−2.5519	22.3877
318.1	−2.4230	22.0772
323.1	−2.2459	21.4434
	$Fe_2(SO_4)_3$ 0.500 M (A) + KBr (B) + H_2O (C)	
293.1	−2.4684	20.6447
298.1	−2.2875	18.9901
303.1	−2.1677	16.7642
308.1	−2.2818	22.0319
313.1	−2.2639	22.3817
318.1	−1.9805	20.4256
323.1	−1.9331	20.0322

For each $Fe_2(SO_4)_3$ concentration and temperature, the measured kinematic viscosities of the solutions containing potassium salts were fitted with the equation proposed by Azfal et al. (1989)

$$\nu = \nu_0\, e^{(C_B w_B + D_B w_B^2)} \qquad (3)$$

where ν is the kinematic viscosity, ν_0 is given by eq 1, w_B is the mass fraction of the potassium salt, and C_B and D_B are the optimized constants. The values of the fitted parameters C_B and D_B are listed for each $Fe_2(SO_4)_3$ concentration and temperature in Tables 5 (for KNO_3) and 6 (for KBr). With these values of C and D, eq 3 fits the experimental data to within ±0.9% (see Figures 1 and 2). No theoretical equation predicting viscosity in terms of both potassium salt concentration and temperature was found to fit the experimental data with reasonable accuracy.

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