Journal of Engineering Physics and Thermophysics, Vol. 80, No. 6, 2007

DYNAMIC VISCOSITY OF AQUEOUS SOLUTIONS OF SALTS AT HIGH TEMPERATURES, PRESSURES, AND CONCENTRATIONS

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UDC 541.135

A generalized formula for obtaining calculated values of the dynamic viscosity of aqueous solutions of salts is presented. With the use of this formula new values of the dynamic viscosity of aqueous solutions of salts $BaCl_2$, KCl, KNO_3, K_2CO_3, $LiNO_3$, Li_2SO_4, $MgCl_2$, and NaCl at high state parameters have been obtained.

Introduction. The dynamic viscosity of aqueous solutions of salts at high state parameters has for a long time remained little understood. Analysis of the experimental data in this field has shown that at high pressures the viscosity has been studied for a small number of various aqueous solutions of salts at pressures of up to 40 MPa and that there are no reliable formulas for obtaining adequate data on the dynamic viscosity of aqueous solutions of salts at high pressures. The aim of the present work was to obtain a formula for calculating the values of the dynamic viscosity at high state parameters.

The new generalized formula for obtaining calculated values of the dynamic viscosity of aqueous solutions of salts in the ranges of temperatures from 333 to 473 K, pressures from 0.1 to 100 MPa, and concentrations from 0 to 25 mass % has the form

$$\eta (P, T, c) = \eta (P_s, T, c)\left[\left(1.800\,\frac{\rho (P, T)}{\rho (P_s, T)} - 0.8000\right) - 3.000\cdot10^{-8} PTc\right] + 1.200\cdot10^{-4}\,\frac{PT}{P_1T_1}\,. \tag{1}$$

Using formula (1), we have calculated the values of the dynamic viscosity of various aqueous solutions of salts — $BaCl_2$, KNO_3, KCl, K_2CO_3, $LiNO_3$, Li_2SO_4, $MgCl_2$, and NaCl at high state parameters (Tables 1–7). They agree with the experimental data [1–14] in the temperature range 333–473 K, the pressure range 0.1–40 MPa, and the concentration range 0–25 mass % within 1.5%. It should be noted that the dynamic viscosity of aqueous solutions of salts was investigated in [1–3, 5–8, 13] at pressures from 0.1 to 40 MPa, and in [4, 9–12, 14] at pressures from 0.1 to 30 MPa.

The values of the dynamic viscosity of water calculated by the new generalized formula (1) in the temperature range 348–473 K and the pressure range 0.1–300 MPa were compared to the existing standard reference data [15]. This comparison has shown that the deviation of the calculated values from the standard data is less than 1.6%.

Equality has been established between the homogeneous ratios of the thermophysical quantities near the saturation line of water and aqueous solutions of salts at equal temperatures under the conditions at $0.1 \le P \le 10$ MPa, $333 \le T \le 473$ K, and $0 \le c \le 25$ mass %:

$$\frac{\lambda (P \le 10, T)}{\lambda (P_s, T)} = \frac{\eta (P \le 10, T)}{\eta (P_s, T)} = \frac{\lambda (P \le 10, T, c \le 25)}{\lambda (P_s, T, c \le 25)} = \frac{\eta (P \le 10, T, c \le 25)}{\eta (P_s, T, c \le 25)}\,. \tag{2}$$

Table 8 presents the values of the ratios between the homogeneous thermophysical quantities near the saturation line. Their numerical values at equal temperatures can be taken as equal (the spread is less than 0.4%) for the temperature range 333–473 K. However, with increasing pressure, temperature, and concentration this equality is disturbed.

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TABLE 1. Dynamic Viscosity Values Calculated by Formula (1) for the $Li_2SO_4 + H_2O$ System at High State Parameters

T, K	P, MPa					
	P_s	20	40	60	80	100
			c = 1.0874 mass %			
331.86	497.8	506.0	513.3	522.1	529.4	536.6
347.05	400.6	407.8	414.7	421.1	427.6	433.6
400.84	228.3	233.9	238.4	243.0	247.6	252.0
420.67	195.6	200.7	205.6	210.2	214.8	218.9
449.55	160.7	165.6	170.2	174.7	179.1	183.0
473.25	139.8	144.9	149.6	154.1	158.5	162.5
			c = 2.9864 mass %			
329.44	563.0	572.2	580.4	589.6	598.3	605.8
351.04	412.1	419.1	425.7	432.7	438.9	445.7
375.75	309.9	315.7	321.3	327.1	332.4	337.3
399.95	247.3	252.7	257.6	262.8	267.4	271.9
423.55	205.5	210.6	215.5	220.5	224.6	229.1
449.35	172.6	177.6	182.5	187.0	191.4	195.6
475.55	147.6	152.7	157.7	162.2	166.5	170.7
			c = 5.7996 mass %			
331.27	627.5	637.1	646.0	656.3	664.6	672.9
349.55	479.7	487.7	494.8	502.4	509.4	516.0
372.13	365.8	372.5	378.6	385.0	391.0	396.3
401.73	276.9	282.6	287.9	293.3	298.4	303.0
424.55	230.2	235.5	240.7	245.9	250.6	255.3
446.35	197.2	202.4	208.0	212.9	217.9	221.9
468.13	172.2	177.8	183.4	188.2	193.1	197.5
			c = 8.8670 mass %			
348.95	567.4	576.2	584.9	593.2	600.8	607.9
397.35	330.4	336.6	342.9	348.8	354.4	359.3
424.05	265.5	271.5	277.4	282.8	287.9	292.6
449.15	221.7	227.5	233.4	238.7	243.7	247.9

Note. The data agree with the experimental data of [4] within 1.4%.

TABLE 2. Dynamic Viscosity Values Calculated by Formula (1) for the $NaCl + H_2O$ System at High State Parameters

T, K	P, MPa					
	P_s	20	40	60	80	100
			c = 5 mass %			
373.15	320.4	326.4	332.1	337.8	339.6	347.9
423.15	209.8	215.0	219.8	224.6	229.0	233.3
473.15	155.9	161.2	166.3	171.0	175.4	179.7
			c = 10 mass %			
373.15	362.1	368.4	374.4	380.0	385.6	390.8
423.15	237.9	243.2	248.5	253.3	257.9	262.2
473.15	175.8	181.3	186.9	191.5	196.3	200.6
			c = 15 mass %			
373.15	412.3	418.9	424.8	431.1	436.9	441.9
423.15	270.2	275.8	281.1	286.5	291.0	295.5
473.15	200.2	206.1	211.7	216.8	221.8	226.3
			c = 20 mass %			
373.15	469.5	476.5	482.5	489.1	494.7	500.3
423.15	303.8	309.7	315.2	320.5	325.2	329.8
473.15	224.9	231.0	237.1	242.3	247.2	251.9

Note. The data agree with the experimental data of [13] within 1.4%.

TABLE 3. Dynamic Viscosity Values Calculated by Formula (1) for the $LiNO_2 + H_2O$ System at High State Parameters

T, K	P, MPa					
	P_s	30	40	60	80	100
			c = 2 mass %			
348.15	389.2	399.4	402.5	409.2	415.1	421.0
373.15	292.6	300.9	303.8	309.3	314.3	319.3
398.15	232.7	240.4	242.8	247.4	252.1	256.6
423.15	191.5	198.7	201.2	205.8	209.9	214.0
448.15	162.0	168.8	171.4	175.9	180.4	184.1
473.15	139.7	147.1	149.5	153.9	158.2	162.1
			c = 4 mass %			
348.15	405.7	415.9	419.1	425.8	432.2	437.9
373.15	306.1	314.4	317.3	322.8	328.0	333.2
398.15	244.0	251.7	254.2	259.1	263.7	268.0
423.15	201.4	208.7	211.3	215.9	220.2	224.4
448.15	171.1	178.0	180.9	185.4	189.9	193.8
473.15	147.9	155.4	158.0	162.5	166.8	170.9
			c = 6 mass %			
348.15	423.1	433.3	436.6	443.4	449.7	455.6
373.15	320.0	328.7	333.4	337.1	342.5	347.5
398.15	256.0	263.8	266.4	271.4	276.2	280.5
423.15	211.9	219.3	222.0	226.6	231.0	235.4
448.15	180.4	187.4	190.5	195.0	199.7	203.5
473.15	156.4	164.0	166.8	171.4	175.8	179.9
			c = 8 mass %			
348.15	441.3	452.4	455.3	461.9	468.0	474.2
373.15	334.8	343.5	346.3	352.2	357.8	362.4
398.15	268.5	276.3	279.0	284.0	289.0	293.1
423.15	222.9	230.6	233.2	237.8	242.3	246.7
448.15	190.2	197.5	200.5	205.2	209.7	213.6
473.15	165.3	173.1	175.8	180.6	185.2	189.3

Note. The data agree with the experimental data of [14] within 1.2%.

TABLE 4. Dynamic Viscosity Values Calculated by Formula (1) for the $KNO_2 + H_2O$ System at High State Parameters

T, K	P, MPa					
	P_s	30	40	60	80	100
			c = 2 mass %			
348.15	381.5	391.6	394.6	401.2	407.0	412.8
373.15	287.3	295.5	298.3	303.8	309.7	313.6
398.15	228.8	236.4	238.7	243.3	247.9	252.3
423.15	188.8	196.0	198.4	203.0	207.0	211.1
448.15	160.4	167.1	169.8	174.2	178.7	182.3
473.15	138.9	146.3	148.7	153.0	157.3	161.2
			c = 4 mass %			
348.15	385.6	395.4	398.4	404.7	410.9	416.4
373.15	291.4	299.4	302.2	307.5	312.5	317.4
398.15	233.0	240.5	242.8	247.5	252.0	256.2
423.15	193.0	200.1	202.6	207.0	211.1	215.3
448.15	164.4	171.1	173.9	178.3	182.7	186.4
473.15	151.6	159.2	161.9	166.5	170.8	175.0
			c = 6 mass %			
348.15	389.8	399.3	402.4	408.7	414.6	420.0
373.15	295.8	303.9	306.5	311.8	316.8	321.6
398.15	237.4	244.7	247.1	251.9	256.4	260.4
423.15	197.2	204.2	206.7	211.1	215.3	219.4
448.15	168.6	175.3	178.2	182.4	186.9	190.5
473.15	146.8	154.1	156.7	161.1	165.3	169.2
			c = 8 mass %			
348.15	394.1	403.3	406.8	412.8	418.3	423.9
373.15	300.4	308.3	310.9	316.3	321.4	325.6
398.15	242.0	249.2	251.6	256.2	260.8	264.7
423.15	201.6	208.7	211.1	215.3	219.6	223.6
448.15	171.8	179.6	182.4	186.7	190.9	194.6
473.15	151.0	158.3	160.8	165.3	169.6	173.4

Note. The data of Table 4 agree with the experimental data of [14] within 1.2%.

TABLE 5. Dynamic Viscosity Values Calculated by Formula (1) for the $MgCl_2 + H_2O$ System at High State Parameters

T, K	P, MPa					
	P_s	30	40	60	80	100
	c = 2 mass %					
348.15	408.2	418.9	422.1	429.1	435.2	441.4
373.15	307.7	316.4	319.3	325.2	330.3	335.6
398.15	245.3	253.3	255.8	260.7	265.6	270.2
423.15	202.2	209.8	212.3	217.2	221.4	225.7
448.15	171.2	178.3	181.1	185.7	190.4	194.2
473.15	147.4	155.1	157.6	162.2	166.7	170.8
	c = 4 mass %					
348.15	446.5	457.6	461.1	468.2	475.3	481.5
373.15	335.9	344.9	348.1	354.0	359.6	365.2
398.15	267.4	275.7	278.4	283.6	288.6	293.3
423.15	220.2	228.1	230.8	235.8	240.3	244.9
448.15	186.3	193.7	196.8	201.6	206.4	210.5
473.15	160.3	168.3	171.1	175.9	180.4	184.7
	c = 6 mass %					
348.15	486.4	497.9	501.7	509.3	516.5	523.2
373.15	365.5	375.2	378.3	384.6	390.6	396.3
398.15	290.5	299.2	302.0	307.6	312.9	317.6
423.15	239.0	247.2	250.1	255.2	260.0	264.9
448.15	201.9	209.6	212.9	217.8	222.9	227.1
473.15	173.7	182.0	185.0	190.0	194.7	199.2
	c = 8 mass %					
348.15	528.0	539.9	544.4	552.2	559.3	566.5
373.15	396.2	406.2	409.5	416.3	422.7	428.0
398.15	314.5	323.4	326.5	332.2	337.8	342.6
423.15	258.5	267.2	270.1	275.3	280.4	285.3
448.15	218.3	226.4	229.8	235.1	240.1	244.4
473.15	187.6	196.2	199.2	204.5	209.6	214.1

Note. The data agree with the experimental data of [14] within 1.2%.

TABLE 6. Dynamic Viscosity Values Calculated by Formula (1) for the $BaCl_2 + H_2O$ System at High State Parameters

T, K	P, MPa					
	P_s	30	40	60	80	100
	c = 2 mass %					
348.15	390.2	400.5	403.6	410.3	416.2	422.1
373.15	295.4	303.8	306.6	312.3	317.3	322.3
398.15	236.4	244.2	246.6	251.3	256.1	260.6
423.15	195.6	203.0	205.4	210.2	214.3	218.5
448.15	166.3	173.2	175.9	180.5	185.1	188.8
473.15	143.8	151.4	153.8	158.3	162.7	166.7
	c = 4 mass %					
348.15	418.5	429.0	432.3	439.0	445.7	451.6
373.15	317.5	326.1	329.1	334.8	339.1	345.5
398.15	254.5	262.5	265.1	270.1	274.9	279.4
423.15	210.9	218.5	221.2	226.0	230.4	234.8
448.15	179.4	186.6	189.6	194.3	198.9	202.9
473.15	155.0	162.7	165.5	170.2	174.6	178.8
	c = 6 mass %					
348.15	449.4	460.1	463.6	470.8	477.5	483.7
373.15	341.8	351.0	353.8	359.9	365.5	370.9
398.15	274.4	282.7	285.4	290.7	295.8	300.3
423.15	227.6	235.5	238.3	243.2	247.8	252.5
448.15	193.7	201.1	204.4	209.1	214.1	218.1
473.15	167.4	175.5	178.4	183.2	187.8	192.2
	c = 8 mass %					
348.15	483.3	494.3	498.5	505.6	512.3	518.9
373.15	368.3	377.7	380.8	387.2	393.2	398.2
398.15	296.1	304.6	307.5	312.9	318.4	322.8
423.15	245.9	254.3	257.0	262.0	266.9	271.6
448.15	209.2	217.1	220.3	225.4	230.2	234.5
473.15	180.9	189.3	192.2	197.3	202.3	206.7

Note. The data agree with the experimental data of [14] within 1.2%.

TABLE 7. Dynamic Viscosity Values Calculated by Formula (1) for the aqueous solutions of salts NaCl, KCl, and K_2CO_3 at High State Parameters

T, K	P, MPa					
	P_s	30	40	60	80	100
			$NaCl + H_2O$ c = 24.006 mass %			
333.15	856	870	874	884	893	900
353.15	654	666	669	676	683	689
374.15	524	534	537	543	549	554
			$KCl + H_2O$ c = 10.049 mass %			
333.15	498	509	512	520	527	533
352.65	389	399	402	407	413	418
			c = 15.732 mass %			
333.15	525	535	539	546	553	559
352.65	413	423	426	431	436	441
423.15	230	237	240	245	249	253
			c = 20.700 mass %			
333.15	557	567	570	578	584	590
352.15	442	451	454	459	464	470
423.65	247	254	257	261	265	269
			c = 24.671 mass %			
333.15	579	587	591	598	604	610
352.15	465	473	476	481	486	491
374.15	379	386	389	393	398	402
421.65	267	274	276	280	284	288
			$K_2CO_3 + H_2O$ c = 20.196 mass %			
333.15	852	868	871	882	892	900
347.65	705	718	723	731	739	746
			c = 25.280 mass %			
333.15	1022	1038	1043	1055	1065	1074
348.15	835	850	854	863	872	879

Note. 1) The data at pressures of 0.1–30 MPa agree with the experimental data of [9–11] within 1%. 2) The dynamic viscosity values near the saturation line at temperatures above 373 K have been obtained by formula (2) with account for the data at P = 10 MPa from [9–11].

TABLE 8. Ratios Between the Homogeneous Thermophysical Quantities Near the Saturation Line

T, K	$\frac{\lambda(P=10, T)}{\lambda(P_s, T)}$	$\frac{\eta(P=10, T)}{\eta(P_s, T)}$	$\frac{\lambda(P=10, T, c=25)}{\lambda(P_s, T, c=25)}$	$\frac{\eta(P=10, T, c=25)}{\eta(P_s, T, c=25)}$
273.15	1.009			
293.15	1.008		1.012	
313.15	1.008			
333.15	1.008	1.005	1.009	1.007
353.15	1.008	1.007		1.008
373.15	1.009	1.009	1.009	1.008
393.15	1.009	1.011		1.009
413.15	1.010	1.012		1.010
433.15	1.012	1.014		1.013
453.15	1.012	1.015		1.014
473.15	1.014	1.016	1.013	1.016

Note. In the calculations, we used the data on the water viscosity from [15], on the heat conductivity of water from [16], on the heat conductivity of the $NaNO_3 + H_2O$ system from [18], and on the viscosity of the $KF + H_2O$ system from [6].

In the calculations by the generalized formula (1), the necessary data on the dynamic viscosity of the water solutions of salts near the saturation line for the temperature range 333–473 K were taken from [1–14], and for higher temperatures they were obtained from the equality of the homogeneous ratios between the thermophysical quantities at equal temperatures by formula (2) with account for the experimental data of [1–14] at $P = 10$ MPa and at equal temperatures and concentrations.

CONCLUSIONS

1. The generalized formula (1) can be used to obtain calculated values of the dynamic viscosity of water and aqueous solutions of salts in the temperature range 333–473 K, the pressure range 0.1–100 MPa, and the concentration range 0–25 mass % with the use of data on the viscosity of aqueous solutions of salts near the saturation line.

2. Equality of the homogeneous ratios between the thermophysical quantities near the saturation line of water and aqueous solutions of salts at equal parameters has been established.

3. The error of the dynamic viscosity values of the aqueous solutions of salts calculated by formula (1) is 1.7%.

4. Formula (2) can be used if reliable data on the dynamic viscosity of aqueous solutions of salts on isobaric lines of $0.1 \le P \le 10$ MPa at temperatures $333 \le T \le 473$ K and concentrations $0 \le c \le 25$ mass % are available.

NOTATION

c, concentration, mass %; P, pressure, MPa; P_1, pressure equal to 1 MPa; P_s, saturation pressure, MPa; T, temperature, K; T_1, temperature equal to 1 K; η, dynamic viscosity coefficient, μPa·sec; λ, heat conductivity coefficient, W/(m·K); ρ, water density [17], kg/m^3.

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