ISSN 1070-4272, Russian Journal of Applied Chemistry, 2007, Vol. 80, No. 2, pp. 213–220. © Pleiades Publishing, Ltd., 2007.
Original Russian Text © G.G. Aseev, I.M. Ryshchenko, A.S. Savenkov, 2007, published in Zhurnal Prikladnoi Khimii, 2007, Vol. 80, No. 2, pp. 213–220.

PHYSICOCHEMICAL STUDIES OF SYSTEMS AND PROCESSES

Equations and Determination of Physicochemical Properties of Ammonium Sulfate-Nitrate Solutions

G. G. Aseev, I. M. Ryshchenko, and A. S. Savenkov

Khar'kovskii Politekhnicheskii Institut National Technical University, Kharkov, Ukraine

Received July 6, 2005; in final form, June 2006

Abstract—Theoretical and correlation equations for calculation of multicomponent systems were considered in terms of a previously developed theory of ion–ion interactions in steady- and nonsteady-state processes for the example of ammonium sulfate-nitrate solutions formed from effluent gases of thermal power plants.

DOI: 10.1134/S1070427207020097

Effluent gases of thermal power plants contain a significant amount of sulfur dioxide (~7 g m^{-3}) and nitrogen oxides (~1.5 g m^{-3}), which are discharged into the atmosphere and contaminate air, soil, and water basins. Previously a new technology for manufacture of ammonium sulfate–nitrate (ASN) fertilizers from these contaminants has been developed [1–3]. The technology includes introduction of gaseous ammonia, electron-beam processing of dusty effluent gases, absorption of the forming SO_3 and NO_2 by water, concentration of ASN solutions, evaporation, and granulation.

Development of new technologies and choice of the optimal ways of utilization of industrial waste require that thermodynamics, kinetics, and various physicochemical parameters should be known. The technology suggested requires particularly reliable and authentic data on physicochemical properties of concentrated solutions of inorganic substances.

The theory of interparticle interactions in steady-state processes in concentrated electrolyte solutions [4] and some implications of this theory [5] were used to suggest methods for determination of physicochemical parameters of multicomponent systems. The following properties of the solutions were analyzed: density, specific heat, thermal conductivity, water vapor pressure over solution, activity of water, surface tension, dynamic viscosity coefficient, electrical conductivity, and boiling and freezing points.

The present study is devoted to analysis of the physicochemical properties of solutions of multicomponent systems based on $(NH_4)_2SO_4$ and NH_4NO_3, with minor additions of NH_4HSO_3, NH_4HSO_4, $(NH_4)_2SO_3$, and NH_4NO_2. The concentrations of the components in solutions was varied from 10 to 70 wt % at an $(NH_4)_2SO_4/NH_4NO_3$ ratio equal to 4 and temperatures of 25–80°C.

The density of a multicomponent solution was calculated by the formula

$$\rho = \rho_0 + \sum_{i=1}^{h} c_i(A_{1i} + A_{2i}t + A_{3i}c_i), \quad (1)$$

where ρ is the solution density (kg m^{-3}); ρ_0, water density (kg m^{-3}); h, number of solution components; c, electrolyte concentration (wt %); t, temperature (°C); and A_{ij}, coefficients found by processing by methods of regression analysis of the authors' own data and those published in the literature for a large number of electrolytes [5]. The values of these coefficients for the components of the ASN solution are listed in Table 1.

Table 1. Coefficients of Eq. (1)

Electrolyte	A_{1i}	A_{2i}	A_{3i}	c, wt %	t, °C	S_ρ,* kg m^{-3}	Δ,* %
NH_4NO_3	4.1148	–0.0101	0.0165	0–70	0–100	4.15	0.26
$(NH_4)_2SO_4$	5.8719	–0.0012	–0.0020	0–70	0–100	1.89	0.13

* S_ρ is the root-mean-square error, and Δ, average relative error of calculation.

Table 2. Density ρ of ASN solutions

c, wt %	ρ, kg m^{-3}, at indicated temperature, °C						
	25	30	40	50	60	70	80
10	1052.4	1050.9	1047.5	1043.2	1038.3	1032.8	1026.8
20	1107.5	1106.1	1102.6	1098.4	1093.5	1088.0	1082.0
30	1162.6	1161.2	1157.8	1153.6	1148.6	1143.1	1137.1
40	1217.8	1216.4	1212.9	1208.6	1203.7	1198.2	1192.2
50	1272.5	1271.4	1268.0	1263.7	1258.8	1253.3	1247.3
60	1327.9	1326.5	1323.0	1318.8	1313.9	1308.3	1302.3
70	1383.0	1381.6	1378.1	1373.8	1368.9	1363.4	1357.3

Table 3. Coefficients of Eq. (3)

Electrolyte	B_{1i}	$B_{2i} \times 10^2$	$B_{3i} \times 10^2$	$B_{4i} \times 10^3$	c, wt %	t, °C	S_{C_p}, J kg^{-1} K^{-1}	Δ, %
NH_4NO_3	–39.21	31.0495	–19.0210	–2.0051	4–16	20–10	13.76	0.25
$(NH_4)_2SO_4$	–55.40	5.3285	96.0142	0.3568	0–15	10–10	10.20	0.1
	–43.30	4.3392	21.5319	0.0312	15–60	10–10	11.46	0.29

The density of water (kg m^{-3}) on the saturation line at 0–150°C was calculated with a relative error of 4.8×10^{-3}% by the formula

$$\rho_0 = 999.810745 + R_1 t^* + R_2 t_*^{1.5} + R_3 t_*^2 + R_4 t_*^{2.5} + R_5 t_*^3 + R_6 t_*^{3.5} + R_7 t_*^4 + R_8 t_*^{4.5}, \qquad (2)$$

where $t^* = 0.01t$, $R_1 = 15.910174$, $R_2 = -73.840671$, $R_3 = 141.693443$, $R_4 = -297.162815$, $R_5 = 160.758796$, $I\mathrm{R}_6 = 146.727674$, $R_7 = -194.580793$, $R_8 = 58.847919$.

The results obtained in calculating the density of the ASN solution are listed in Table 2.

The specific heat of the multicomponent solution, C_p (J kg^{-1} K^{-1}) can be calculated by the formula

$$C_p = C_{p0} + \sum_{i=1}^{k} (B_{1i} + B_{2i} c_i + B_{3i} t + B_{4i} t^2) c_i. \qquad (3)$$

Here, C_{p0} is the specific heat of water (J kg^{-1} K^{-1}); $\tilde{c}_i$, concentration of ith component in a binary isopiestic solution (wt %); t, temperature (°C); c_i, concentration of ith component in the multicomponent solution (wt %); k, number of the solution components; and B_{ni}, coefficients found by processing by methods of regression analysis of the authors' own data and those published in the literature for a large number of electrolytes [6, 7]. The values of these coefficients for the components of the ASN solution are listed in Table 3.

The specific heat of water (J kg^{-1} K^{-1}) on the saturation line at $0°C \le t < 40°C$ was calculated with a root-mean-square and average relative calculation errors of 3.95 J kg^{-1} K^{-1} and 0.035%, respectively, by the formula

$$C_{p0} = 4.21703 - 0.068372 t_*^{0.5} - 0.193808 t_*^{1.5} + 0.340252 t_*^2, \qquad (4)$$

where $t_* = 0.01t$.

In the temperature range $40°C \le t < 250°C$, the specific heat of water was found by the formula

$$C_{p0} = 4.178232 - 0.200822 t_*^{2.5} + 0.551896 t_*^{1.3} - 0.435824 t_*^{3.5} + 0.123167 t_*^4. \qquad (5)$$

The value of $\tilde{c}_i$ was calculated as

$$\tilde{c}_i = E_i^{-1} \sum_{j=1}^{k} E_j c_i. \qquad (6)$$

Here E_i is a coefficient characterizing the vapor pressure over solution, which can be found from the dependence [5, 7]:

$$E_i = (1 - a_w^s) c_i^s, \qquad (7)$$

where a_w^s and c_i^s are, respectively, the activity of water and the mass fraction of a saturated solution of a separate component of the system under consideration at a given temperature.

Table 4. Specific heat of ASN solutions, C_p

c, wt %	C_p, J kg^{-1} K^{-1} at indicated temperature, °C						
	25	30	40	50	60	70	80
10	4175.1	4173.3	4173.3	4174.9	4178.0	4182.6	4189.0
20	4170.2	4168.3	4167.8	4168.9	4171.5	4175.5	4181.3
30	4165.4	4163.2	4162.3	4163.0	4164.9	4168.5	4173.6
40	4160.6	4158.2	4156.8	4157.0	4158.4	4161.4	4165.9
50	4155.7	4153.1	4151.3	4151.0	4151.9	4154.3	4158.2
60	4150.9	4148.1	4145.8	4145.0	4145.4	4147.2	4150.5

Table 5. Coefficients of Eq. (8)

Electrolyte	$-\beta \times 10^3$	c, wt %	t, °C	$S_\lambda \times 10^3$, W m^{-1} K^{-1}	Δ, %	Electrolyte	$-\beta \times 10^3$	c, wt %	t, °C	$S_\lambda \times 10^3$, W m^{-1} K^{-1}	Δ, %
NH_4NO_3	1.1598	0–50	10–100	5.97	0.79	$(NH_4)_2SO_4$	2.3668	0–30	10–90	9.69	1.22

Table 6. Thermal conductivity λ of ASN solutions

c, wt %	λ, W m^{-1} K^{-1} at indicated temperature, °C						
	25	30	40	50	60	70	80
10	0.594	0.602	0.617	0.630	0.640	0.649	0.656
20	0.581	0.589	0.604	0.616	0.626	0.635	0.641
30	0.569	0.576	0.590	0.602	0.613	0.621	0.627

The results obtained in calculating the specific heat of the ASN solution are listed in Table 4.

The thermal conductivity of multicomponent electrolyte solutions was calculated by the formula

$$\lambda = \lambda_0\left(1 + \sum_{i=1}^{k}\beta_i c_i\right). \qquad (8)$$

Here, λ is the thermal conductivity of the solution (W m^{-1} K^{-1}); λ_0, thermal conductivity of water (W m^{-1} K^{-1}); c_i, concentration of ith component in the multicomponent solution (wt %); k, number of solution components; and β_i, coefficients found by processing by methods of regression analysis the authors' own data and those published in the literature for a large number of electrolytes [8]. The values of these coefficients for the components of the ASN solution are listed in Table 5.

The thermal conductivity of water on the saturation line at temperatures of 0 to 135°C was approximated with a root-mean-square calculation error S_λ = 0.29 W m^{-1} K^{-1} and average relative calculation error Δ = 0.03% with the polynomial

$$\lambda_0 = 10^{-3}(L_0 + L_1T^* + L_2T_*^{1.5} + L_3T_*^{2.5} + L_4T_*^3), \qquad (9)$$

where L_0 = 560.971778, L_1 = 178.153112, L_2 = 59.731618, L_3 = –245.008302, L_4 = 124.973313, T^* = 0.01t, and t is temperature (°C).

The results of calculation of the thermal conductivity of an ASN solution are listed in Table 6.

The water vapor pressure (Pa) over a multicomponent electrolyte solution was calculated by the equation

$$P = P_0 \exp\left(2.3026 \sum_{i=1}^{k} m_i P_i^*\right), \qquad (10)$$

where P_0 is the water vapor pressure over pure water (Pa); m_i, mass concentration of the electrolyte in

Table 7. Coefficients of Eq. (15)

Coefficient	c, wt %	t, °C	Δ, %	Coefficient	c, wt %	t, °C	Δ, %
NH_4NO_3 electrolyte				$(NH_4)_2SO_4$ electrolyte			
$W_{0i} = -9.0900 \times 10^{-3}$	2–50	0–100	0.46	$W_{0i} = -1.6377 \times 10^{-2}$	2–50	0–100	0.17
$W_{1i} = 6.2000 \times 10^{-5}$				$W_{1i} = 9.9500 \times 10^{-5}$			
$W_{2i} = 7.5700 \times 10^{-5}$				$W_{2i} = -2.3900 \times 10^{-5}$			
$W_{3i} = -9.0000 \times 10^{-7}$				$W_{3i} = -8.0000 \times 10^{-7}$			
$W_{4i} = -7.6000 \times 10^{-6}$				$W_{4i} = -2.0900 \times 10^{-5}$			
$W_{5i} = 0.1000 \times 10^{-6}$				$W_{5i} = 2.0000 \times 10^{-7}$			

Table 8. Water vapor pressure P over an ASN solution

c, wt %	P, Pa, at indicated temperature, °C						
	25	30	40	50	60	70	80
10	3079	4127	7179	12010	19394	30329	46065
20	2970	3982	6931	11597	18727	29279	44445
30	2829	3794	6606	11057	17856	27914	42366
40	2643	3543	6168	10325	16678	26083	39611
50	2385	3194	5554	9294	15022	23530	35823
60	2014	2689	4655	7778	12590	19809	30382

the solution (mol kg^{-1}); k, number of solution components; and P_i^*, correction for the decrease in the water vapor pressure over the multicomponent electrolyte solution.

The water vapor pressure over pure water on the saturation line is calculated with root-mean-square and average relative errors of 39.54 Pa and 0.006% by the formula

$$P_0 = P_c \exp B. \tag{11}$$

Here, P_c is the critical pressure equal to 2.2064×10^7 Pa and B is given by

$$B = T_c A/T, \tag{12}$$

where T_c is the critical temperature equal to 647.14; T, temperature (K); and A is found from the following dependence at temperature of 0 to 100°C:

$$A = A_0 + A_1 T_*^{1.5} + A_2 T_*^3 + A_3 T_*^{3.5}, \tag{13}$$

$A_0 = -0.595684$, $A_1 = -11.039345$, $A_2 = 17.449275$, $A_3 = -16.028445$,

$$T^* = 1 - T/T_c. \tag{14}$$

The value of P_i^* in Eq. (10) was found using the formula

$$P_i^* = W_{0i} + W_{1i}t_i + W_{2i}m_i + W_{3i}t_i^2 + W_{4i}t_i m_i + W_{5i}t_i^2 m_i, \tag{15}$$

where the coefficients W_{ji} are found by processing by methods of regression analysis of the authors' own data and those published in the literature for a large number of electrolytes [5]. The values of these coefficients for the components of the ASN solution are listed in Table 7.

The results obtained by calculating the water vapor pressure over an ASN solution are listed in Table 8.

The activity of water can be calculated by theoretical and semiempirical equations reported in [4, 5], where various calculation examples were demonstrated. In view of the limited volume of the present communication, the following formula can be recommended in the given case

$$a_w = \exp\left(2.3026 \sum_{i=1}^{k} m_i P_i^*\right). \tag{16}$$

Table 9. Activity a_w of water over an ASN solution

c, wt %	a_w at indicated temperature, °C						
	25	30	40	50	60	70	80
10	0.9725	0.9729	0.9735	0.9737	0.9737	0.9733	0.9727
20	0.9379	0.9387	0.9397	0.9403	0.9402	0.9396	0.9385
30	0.8935	0.8944	0.8957	0.8964	0.8964	0.8958	0.8946
40	0.8345	0.8352	0.8364	0.8371	0.8373	0.8371	0.8364
50	0.7531	0.7530	0.7531	0.7535	0.7542	0.7551	0.7564
60	0.6360	0.6339	0.6312	0.6306	0.6321	0.6357	0.6416

Table 10. Surface tension σ of ASN solutions

c, wt %	σ, N m^{-1}, at indicated temperature, °C						
	25	30	40	50	60	70	80
10	0.073	0.072	0.071	0.069	0.067	0.066	0.064
20	0.075	0.074	0.073	0.071	0.069	0.067	0.066
30	0.077	0.076	0.075	0.073	0.071	0.070	0.068
40	0.080	0.079	0.078	0.076	0.074	0.072	0.071
50	0.084	0.083	0.082	0.080	0.078	0.076	0.075
60	0.090	0.089	0.088	0.086	0.084	0.082	0.080

Table 11. Coefficients of Eq. (19)

Electrolyte	$A_0 \times 10^3$	$A_1 \times 10^4$	$A_2 \times 10^5$	$A_3 \times 10^6$	c, wt %	t, °C	$S_\eta \times 10^2$	Δ, %
NH_4NO_3	–13.765	3.956	13.88	–2.1	5–40	25–95	1.50	1.32
$(NH_4)_2SO_4$	15.434	0.744	12.29	0.0	0–50	20–90	3.54	1.72

The results obtained by calculating the activity of water over the ASN solution are listed in Table 9.

The surface tension of a multicomponent solution can be calculated by the formula [8]:

$$\sigma = \sigma_0 + 0.049(1 - a_w), \tag{17}$$

where σ is the surface tension of the multicomponent electrolyte solution (N m^{-1}); σ_0, surface tension of water (N m^{-1}); and a_w, activity of water in the multicomponent solution.

The surface tension was calculated with high accuracy for the entire range of existence of water from the data of [9]:

$$\sigma_0 = B\left(\frac{T_0 - T}{T_0}\right)^m \left[1 + b\left(\frac{T_0 - T}{T_0}\right)\right], \tag{18}$$

where $B = 235.6 \times 10^{-3}$, $T_0 = 647.15$, $m = 1.256$ $b = -0.625$.

The results of calculation of the surface tension of ASN solutions are listed in Table 10.

The dynamic viscosity coefficient η (Pa s) of a multicomponent solution was calculated by the formula

$$\eta = \eta_0 \exp V, \tag{19}$$

$$V = \sum_{i=1}^{k} c_i(A_{0i} + A_{1i}t + A_{2i}c_i + A_{3i}t^2),$$

where η_0 is the dynamic viscosity coefficient of water (Pa s); k, number of electrolyte components in the solution; c_i, mass fraction of ith component in the multicomponent solution (%); t, temperature (°C); and A_{ij}, found by processing by methods of regression analysis of the authors' own data and those published in the literature for a large number of electrolytes [10, 11]. The values of these coefficients for the components of the ASN solution are listed in Table 11.

The viscosity of water, η_0 (Pa s), on the saturation line in the temperature range 0–350°C was calcu-

Table 12. Dynamic viscosity coefficient η of ASN solutions

c, wt %	$\eta \times 10^{-3}$, Pa s, at indicated temperature, °C						
	25	30	40	50	60	70	80
10	1.018	0.919	0.762	0.645	0.555	0.483	0.426
20	1.187	1.077	0.904	0.773	0.670	0.589	0.523
30	1.407	1.284	1.089	0.941	0.824	0.730	0.654
40	1.696	1.557	1.335	1.165	1.030	0.920	0.830
50	2.080	1.920	1.665	1.467	1.309	1.179	1.072
60	2.593	2.408	2.110	1.879	1.691	1.537	1.408

lated with root-mean-square and average relative calculation errors of, respectively, 1.19 (Pa s) and 0.07% in the temperature interval 0–200°C by the formula

$$\eta_0 = S_0 + S_1 t + S_2/t + S_3 \exp(-0.1t) + S_4/t^2 + S_5\sqrt{t} + S_6 \ln t, \qquad (20)$$

where $S_0 = 4496.839782$, $S_1 = -4.644252$, $S_2 = -7025.494506$, $S_3 = -159.419139$, $S_4 = 4104.442382$, $S_5 = 316.705387$, and $S_6 = -1486.934219$.

The results of a calculation of the dynamic viscosity coefficient of ASN solutions are listed in Table 12.

The electrical conductivity Λ (S cm^2 mol^{-1}) of a multicomponent electrolyte solution can be calculated using the following theoretical equation [4–6]:

$$\Lambda = \frac{1}{c_{kg}} \sum_{i=1}^{k} \nu_i c_{ki} [\Lambda_i (1 - L_i) + K_{1i} c_{ki}^2]. \qquad (21)$$

Here, c_{kg} is the total molar concentration of the equivalent of the solution components (g-equiv dm^{-3}); k, number of electrolyte components in the solution; ν_i, number of like charges of the electrolyte molecule; c_{ki}, molar concentration of each electrolyte component (mol dm^{-3}); Λ_i^0, limiting molar electrical conductivity of each component of the multicomponent solution in water (S cm^2 mol^{-1}); L_i, parameter of ith component in the solution; and K_{1i}, correction factor for ith component of the solution [4, 5].

In turn, Λ_i^0 was found using the formula

$$\Lambda_i^0 = \lambda_i^0 + \lambda_j^0, \qquad (22)$$

where λ_i^0 and λ_j^0 are the limiting electrical conductivities of cations and anions in water (S cm^2 mol^{-1}).

The limiting molar electrical conductivities of cations and anions in water were calculated using expressions reported in [5].

The parameter L_i was found using the equation

$$L_i = V_{0i} + V_{1i} t + V_{2i} c_{ki} + V_{3i} t c_{ki} + V_{4i} (t c_{ki})^2 + V_{5i} c_{ki}^{0.7} + V_{6i} c_{ki}^{0.7} + V_{7i} (t c_{ki})^{0.5}, \qquad (23)$$

where t is temperature (°C), and V_{ij} are coefficients found by processing by methods of regression analysis of the authors' own data and those published in the literature for a large number of electrolytes [5].

The correction factor K_{1i} was determined by the formula [5]:

$$K_1 = -3.161 \times 10^{17} \frac{(\nu_k z_i)^2 \alpha_a}{\eta_0 \varepsilon (\varepsilon T)^3 (6 - \alpha_a^2)}, \qquad (24)$$

where ν_k is the number of ions in the electrolyte molecule; z_i, cation charge; α_a, theoretical parameter [4, 6]; η_0, viscosity of water (Pa s); ε, dielectric constant; and T, temperature (K).

The value of α_a was found using the expression derived in [4]:

$$\alpha_a = \sinh(\beta/a), \qquad (25)$$

where β is calculated by the formula

$$\beta = \frac{1.6718 \times 10^{-3} |z_i z_j|}{\varepsilon T}. \qquad (26)$$

The value of ε can be calculated with a standard deviation of 0.33 in ε units by the equation [12]:

$$\varepsilon = 1 + (a_1/T^*)\rho + (a_2/T^* + a_3 + a_4 T^*)\rho_*^2 + (a_5/T^* + a_6 T^* + a_7 T_*^2)\rho_*^3 + (a_8/T_*^2 + a_9/T^* + a_{10})\rho_*^4, \qquad (27)$$

where

$$T^* = T/298.15, \quad \rho^* = \rho_0/1000, \qquad (28)$$

and ρ_0 is the density of water (kg m^{-3}).

Table 13. Electrical conductivity Λ of ASN solutions

c, wt %	Λ, S cm^2 mol^{-1}, at indicated temperature, °C						
	25	30	40	50	60	70	80
10	32.81	35.92	42.14	48.47	54.98	61.74	68.78
20	31.13	33.96	39.59	45.27	51.10	57.12	63.38
30	29.36	31.93	37.04	42.17	47.43	52.87	58.52
40	27.69	30.04	34.70	39.39	44.20	49.18	54.37
50	26.15	28.31	32.59	36.91	41.36	45.99	50.82
60	24.74	26.74	30.70	34.72	38.88	43.21	47.75

The coefficients a_i have the following values: $a_1 = 7.62571$, $a_2 = 244.003$, $a_3 = -140.569$, $a_4 = 27.7841$, $a_5 = -96.2805$, $a_6 = 41.7909$, $a_7 = -10.2099$, $a_8 = -45.2059$, $a_9 = 84.6395$, $a_{10} = -35.8644$.

Equation (27) is applicable under the following conditions: temperature 273.15–823.15 K, density 0–1150 kg m^{-3}, pressure 0–500 MPa. The value of a in Eq. (25) is found by the formula

$$a = \chi_f(a_i + a_j), \qquad (29)$$

where $\chi_f = 1$ for electrolytes of the symmetric type and $\chi_f = 2$ for those of the asymmetric type, and distances from the ion center to the oxygen of water for ions in solution and the effective radii of polyatomic ions a_i and a_j (nm) can be found in [5].

The results of calculation of the electrical conductivity of ASN solutions are listed in Table 13.

The boiling point T_b (K) of a multicomponent solution can be calculated with an accuracy acceptable for practical purposes by the modified formula [5]:

$$T_b = 500.2238/[(24.6536 + \ln a_w)^{1/2} - 3.6249], \qquad (30)$$

$$0 < t < 215°\text{C}, \quad S_{T_b} = 0.6 \text{ K},$$

where S_{T_b} is the root-mean-square calculation error (K).

Equation (30) is solved by the method of iterations. First a_w (0.99) is set and T_b is calculated. This value of T_b is used to find a_w, using formulas (10)–(16) or some others. Then, T_b is again calculated [calculation of the vapor pressure over solution with the use of coefficients in formulas (13) and (15) allows a slight extrapolation beyond 100°C]. The number of iterations is 2. Making this number larger impairs the calculation accuracy. Instead of calculating a_w, it is possible to use its experimental values reported in [13] at temperatures below 100°C for many tens of electrolytes, with the activity of water at T_b found by means of a linear approximation. The results of calculation of the boiling points of ASN solutions are presented below (°C):

c, wt%	10	20	30	40	50	60
T_b, °C	100.86	101.97	103.28	105.16	107.97	112.42

The freezing temperature of a multicomponent solution, T_f (K) is commonly found in the entire range of activities of water, using the equation [5]:

$$T_f = \frac{555.316}{2.76375 - \sqrt{\ln a_w^{(25)} + 0.53398}}, \qquad (31)$$

where $\ln a_w^{(25)}$ is the activity of water over solution at 25°C.

The applicability of formula (31) is limited by the lower bound of the interval $|\ln a_w^{(25)}| < 0.53398$, because the expression within the square root should be positive.

The results of calculation of the freezing point of ASN solutions are presented below (°C):

c, wt %	10	20	30	40	50
T_f, °C	−2.58	−5.95	−10.54	−17.19	−27.79

The whole set of the physicochemical studies performed enabled optimal consideration of heat-and-mass exchange processes in the technology for manufacture of a complex integrated fertilizer based on ammonium sulfate and nitrate with microelements from effluent gases discharged by thermal power plants.

CONCLUSIONS

(1) The previously developed theory of ion–ion interactions in steady- and nonsteady-state processes in concentrated electrolyte solutions was used to derive new equations for calculation of physicochemical properties of multicomponent systems of electrolyte

solutions: density, specific heat, thermal conductivity, water vapor pressure over solution, activity of water, surface tension, dynamic viscosity coefficient, boiling and freezing points, and electrical conductivity.

(2) New correlation equations were suggested for determining the density of water, specific heat, thermal conductivity, water vapor pressure over solution, dynamic viscosity of water on the saturation line in a wide range of temperatures and pressures. These equations provide the minimum calculation errors.

(3) The physicochemical properties of ammonium sulfate-nitrate solutions were calculated for a mass fraction of the components equal to 10–70% in the temperature range 25–80°C. This made it possible to recommend the equations under consideration for determining these properties for other multicomponent systems of electrolytes as well.

(4) The set of the physicochemical studies performed enabled optimal consideration of heat-and-mass exchange processes that occur in manufacture of a complex integrated fertilizer based on ammonium sulfate and nitrate with addition of microelements from effluent gases of thermal power plants.

REFERENCES

1. Savenkov, A.S., Ryshchenko, I.M., and Ushakova, N.M., *Vestn. Kharkov. Gos. Politekhn. Univ.*, Kharkov: Kharkov. Gos. Politekhn. Univ., 2000, issue 105, pp. 39–41.
2. Savenkov, A.S., Ryshchenko, I.M., and Ushakova, N.M., *Khimiya i tekhnologiya proizvodstva osnovnoi khimicheskoi produktsii: Trudy NIOKhIM* (Chemistry and Technology of Manufacture of Basic Chemical Products: Trans. NIOKhIM), Kharkov, 2001, vol. 72, pp. 199–203.
3. Savenkov, A.S. and Fanshtein, A.L., *Sbornik nauchnykh trudov "Ekologiya-98"* (Coll. of Sci. Works: "Ecology-98"), Severodonetsk, 1998, pp. 71–72.
4. Aseyev, G.G., *Electrolytes: Interparticle Interactions: Theory, Calculation Methods and Experimental Data.*, New York: Begell House, 1998.
5. Aseev, G.G., Ryshchenko, I.M., and Savenkov, A.S., *Elektrolity: Fiziko-khimicheskie parametry kontsentrirovannykh mnogokomponentnykh sistem: Monografiya* (Electrolytes: Physicochemical Parameters of Concentrated Multicomponent Systems: Monograph), Kharkov: KhPI NTU, 2005.
6. Aseev, G.G., Ryshchenko, I.M., and Savenkov, A.S., *Vopr. Khim. Khim. Tekhnol.*, 2004, no. 4, pp. 61–66.
7. Aseev, G.G., Ryshchenko, I.M., and Savenkov, A.S., *Vestnnik Natsional'nogo tekhnicheskogo universiteta "KhPI": Sbornik nauchykh trudov, Tematicheskii vypusk "Khimiya, khimicheskaya tekhnologiya i ekologiya"* (Journal of KhPI National Technical University, Col. of Sci. Works: Subject Issue "Chemistry, Chemcal Technology, and Ecology)", Kharkov: KhPI NTU, 2001, no. 23, vol. 2, pp. 104–107.
8. Aseyev, G.G., *Electrolytes: Properties of Solutions Methods for Calculation of Multicomponent Systems and Experimental data on Thermal Conductivity and Surface Tension*, New York: Begell House, 1999.
9. Rivkin C.L. and Aleksandrov, A.A., *Teplofizicheskie svoistva vody i vodyanogo para* (Thermal Properties of Water and Water Vapor), Moscow: Energiya, 1980.
10. Aseyev, G.G., *Electrolytes: Transport Phenomena: Methods for Calculation of Multicomponent Solutions and Experimental data on Viscosities and Diffusion Coefficients*, New York: Begell House, 1998.
11. Ryshchenko, I.M., Aseev, G.G., and Savenkov, A.S., *Zbirn. nauk. prats' mizhnar. nauk.-prakt. konf. "Kompleksne vikoristannya sirovini, energo- ta resursozberigayuchi tekhnologii u virobnitstvi neorganichnikh rechovin", 27–29 travnya 2004 r.* (Proc. Int. Sci.-Pract. Conf. "Integrated Use of Raw Materials and Energy- and Resource-Saving Technologies in Manufacture of Inorganic Substances," May 27–29, 2004), Cherkasi: Vertikal', 2004, pp. 126–127.
12. Uematsu, M. and Franck, E.U., *J. Phys. Ref. Data*, 1980, vol. 9, no. 4, pp. 1291–1305.
13. Aseyev, G.G., *Electrolytes, Equilibria in Solutions and Phase Equilibria: Calculation of Multicomponent Systems and Experimental Data on the Activities of Water, Pressure Vapor and Osmotic Coefficients*, New York: Begell House, 1998.