PHYSICAL AND CHEMICAL CHARACTERISTICS OF HYDROTHERMAL HEAT CARRIER OF MUTNOVSKOYE FIELD

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ABSTRACT

The experiments on researching of physical and chemical characteristics of hydrothermal heat carrier of Verhne-Mutnovsky geothermal electric power plant and wells 4E, 014 of Mutnovskoyoe field were carried out. The concentrations of cations and anions, pH, mineralization, ionic strength, conductivity of separate and vapor condensate solutions, concentration of gases in vapor phase of heat carrier were determined. Coefficients in linear dependence of ionic strength from solution mineralization for separate and condensate were established. The dependence of separate conductivity from solution temperature was investigated. The experimental data and theoretical values of conductivity were compared. The sizes and diffusion coefficients of colloidal silica particles were measured by the method of photon correlation spectroscopy. The results obtained in this work can be applied for development of technology of silica extraction and increasing of efficiency of hydrothermal heat carrier using.

INTRODUCTION

Chemical composition of hydrothermal heat carrier is depended on the interaction of water solution with minerals of alumosilicate rocks of hydrothermal systems. This interaction occurs with increased temperature and pressure. Temperature in the deepest parts of the high-temperature systems similar to the system of Mutnovskoe field can reach 250-350°C. When heat carrier rises to the surface in productive wells of geothermal electric power stations part of heat carrier turns into vapour phase because of decrease in pressure. On the surface in separators of the geothermal electric power plant (GeoPP) vapour phase is separated and fed to the turbine for generation of electric power. Presence of vapour phase of hydrogen sulfide in gas composition leads to corrosion of heat equipment of geothermal electric power plant. Higher mineralization of liquid phase of heat carrier (separate) determines one more technical problem – formation of solid deposits in wells, pipes and heat equipment of geothermal electric power plant. Solid deposits of silica make the largest difficulty. In this paper results of researching of the chemical composition and characteristics of heat carrier which are necessary for solving the technical problems of exploitation of geothermal electric power plant are given.

1. CHEMICAL COMPOSITION OF LIQUID AND VAPOUR PHASES OF HYDROTHERMAL HEAT CARRIER

Experiments on researching of physical and chemical characteristics were carried out using hydrothermal separate from productive wells of Verkhne-Mutnovsky geothermal electric power plant and, besides, from wells 014, 4E, 5E, A2 of Mutnovskoe field. pH value of samples of solution at 20°C was within 8.0-9.4, total mineralization – 1.0 – 2.5 g/kg, ionic strength of solution – 10 – 20 mmole/kg. Total content of silica in samples was 650 – 820 mg/kg, concentration of monomeric silica (monomeric orthosilicic acid) corresponded to solubility C_e at the temperature of the experiments. The most experiments were carried out with separate samples from the reinjection pipe-line of Verkhne-Mutnovsky geothermal electric power plant.

Productive wells 048, 049, 055 of Verkhne-Mutnovsky geothermal electric power plant(GeoPP) bring heat carrier to the surface as vapour-water mixture (VWM) with mass vapour content of 0.2-0.3. Mouth binding of productive wells is united in one common collector in which three flows of heat carrier mix. In separators of first and second line at pressure of 0.8 MPa and temperature 170.4°C vapour-water mixture is divided into vapour phase which is fed to the turbines and liquid phase (separate) with consumption of 50-55 kg/s. Separate comes to expander where pressure is about 0.4 MPa, and temperature – near 143.6°C. From expander separate with pressure of 0.4 bar is pumped through two reinjected wells back to the rocks of hydrothermal

field. Heat-exchanger was settled on the reinjection pipe-line of geothermal electric power plant.

Table 1a. Concentrations of anions and cations in hydrothermal separate from reinjection line of Verkhne-Mutnovsky geothermal electric power plant, I_s = 14.218 mmole/kg. n.d.- concentration was not determined, (-)- values were not calculated.

Component	mg/l	mg·equiv/l	
		mg·equiv/l	%mg·equiv/l
Na^+	239.4	10.413	88.044
K^+	42.0	1.074	9.080
Ca^{2+}	1.6	0.0798	0.6747
Mg^{2+}	0.72	0.0592	0.5005
$Fe^{2, 3+}$	<0.1	<0.0053	0.0448
Al^{3+}	0.27	0.033	0.2790
NH_4^+	1.1	0.0609	0.5149
Li^+	0.71	0.102	0.8624
Sum of cations	285.9	11.827	100.0
Cl^-	198.5	5.591	47.664
HCO_3^-	81.0	1.327	11.312
CO_3^{2-}	19.9	0.663	5.652
SO_4^{2-}	192.1	3.9995	34.096
HS^-	4.95	0.15	
H_2S^0	5.92	-	-
F^-	n.d.	n.d.	-
Sum of anions	496.5	11.73	100.0
H_3BO_3	106.9	-	-
$(H_4SiO_4)_t$	1190	-	-
$(H_4SiO_4)_s$	222	-	-
Mineralization M_h,	1638.9	-	-
pH	9.35	-	-

Table 1b. Chemical composition of sample of steam condensate selected from vapour preparation plant of Verkhne-Mutnovsky geothermal electric power plant.

pH = 5.24, specific conductivity σ = 0.0705 mSm/cm.

Units	Cl^-	SO_4^{2-}	HCO_3^-	CO_3^{2-}	NO_2^-	NO_3^-	F^-	Sum
mg/l	2.385	6.00	10.07	0.00	<0.003	0.423	0.00	19.00
mg·equiv/l	0.067	0.125	0.165	0.000	0.000	0.007	0.000	0.364
mg·equiv %	18.00	34.00	46.00	0.00	0.001	2.00	0.00	100.00

Units	Na^+	K^+	Li^+	Ca^{2+}	Mg^{2+}	Fe^{2+}	Fe^{3+}	NH_4^+	Sum
mg/l	0.731	<1.00	<0.03	0.75	0.10	2.108	<0.05	9.00	13.0
Mg·eq/l	0.032	0.000	0.000	0.037	0.008	0.075	0.000	0.500	0.658
mg·eq %	5.00	0.00	0.00	6.00	1.00	11.00	0.00	76.00	100.0

CO_2, mg/l	oxid., mg/l	SiO_2, mg/l	B, mg/l	As, mg/l	$Fe(OH)_3$ mg/l	dry precipitate mg/l	M_h, mg/l
0.00	0.00	4.90	0.00	0.00	< 0.10	39.00	37.00

Table 2a. Data on concentration of gases in composition of vapour phase of heat carrier of well 4E from Mutnovskoe field.

Date	CO_2	H_2S	H_2	CH_4	N_2	Ar	He	Volume gas content	Mouth pressure bar
5.11.98	82.2	10.0	0.62	0.13	6.9	0.16	0.0016	0.015	7.48
7.11.98	68.5	15.7	0.77	0.15	14.5	0.31	0.0018	0.009	8.79
9.11.98	81.7	9.3	0.85	0.22	7.7	0.22	0.0019	0.019	11.2
12.11.98	73.1	14.4	0.80	0.18	11.3	0.22	0.0021	0.014	11.83
13.11.98	67.0	11.4	1.27	0.29	19.7	0.36	0.0035	0.009	4.27
14.11.98	55.9	20.6	1.27	0.34	21.6	0.38	0.0045	0.015	6.31
average	71.4	13.6	0.93	0.22	13.6	0.27	0.0026	0.013	--

Table 2b. Results of chemical analysis of condensate and separate samples from well 4E, mg/kg.

condensate				
date	5.11.98	7.11.98	9.11.98	12.11.98
pH	4.93	5.1	5.3	4.78
NH_4^+	3.1	2.7	3.1	3.1
Na^+	0.02	0.21	0.02	0.03
K^+	0.07	0.2	0.11	0.07
Li^+	<0.01	<0.01	<0.01	<0.01
Ca^+	<0.4	<0.4	<0.4	<0.4
Mg^{2+}	<0.24	<0.24	<0.24	<0.24
$Fe^{2+, 3+}$	<0.3	<0.3	<0.3	<0.3
Al^{3+}	<0.27	<0.27	<0.27	<0.27
Cl^-	<0.7	<0.7	<0.7	<0.7
SO_4^{2-}	3.3	4.8	3.3	6.7
HCO_3^-	6.1	4.88	7.3	3.7
CO_3^{2-}	0.04	0.03	0.03	0.02
F^-	0.04	0.03	0.03	0.02
H_3BO_3	<0.7	<0.7	<0.7	<0.7
H_4SiO_4 (р)	2.4	2.3	2.3	2.3
H_4SiO_4 (к)	3.3	3.3	3.3	3.3
As	0.04	0.06	0.074	0.046
G_s, kg/s	9.1	8.6	7	3.8
G_w, kg/s	17.6	17.6	15.2	7.1

Concentrations of basic components of hydrothermal separate solution selected from the reinjection pipeline of GeoPP are given in table 1a. For comparison table 1B contains data on chemical composition of steam condensate. Table 2a presents data on gas concentration in vapour phase of hydrothermal heat carrier of well 4E obtained in the works of Mutnovskoye field (Potapov V.V., Kashpura V.N., Alekseev V.I., 2001). Data shows, that CO_2, H_2S, N_2 prevail in gas composition of heat carrier. Tables 2b and 2c contains data on chemical composition of separate from well 4E.

Solution of separate from Mutnovskoye field is of chloride-sulphate-sodium-potassium type of hydrothermal solutions. Kurlov's formula of

chemical composition of water which reflects percentage of anions and cations in milligram-equivalents is the following: Cl47.66·SO₄34.09/Na88.04·K9.08.

Dependence of ionic strength I_s (mole/kg) of hydrothermal solution from wells of Mutnovskoe field on mineralization M_h (mg/kg) is expressed by the equation:

$$I_s = A_I \cdot 10^{-6} \cdot M_h, \quad (1)$$

where A_I – is coefficient which is (7.35 – 8.68) mole/mg for separate, and 17.34 mole/mg for vapour condensate.

Table 2c. Results of chemical analysis of condensate and separate samples from well 4E, mg/kg.

separate				
date	5.11.98	7.11.98	9.11.98	12.11.98
pH	9.06	9.09	9.14	9.15
NH_4^+	0.3	0.3	0.3	0.55
Na^+	273	275	271	272
K^+	54	54.5	53.5	54.5
Li^+	1.42	1.43	1.43	1.42
Ca^+	3	3	3	3
Mg^{2+}	<0.24	<0.24	<0.24	<0.24
$Fe^{2+\ 3+}$	<0.3	<0.3	<0.3	<0.3
Al^{3+}	<0.27	<0.27	<0.27	<0.27
Cl^-	244.9	244.9	244.9	244.9
SO_4^{2-}	249.7	249.7	249.7	249.7
HCO_3^-	81.1	80.5	79.3	79.3
CO_3^{2-}	6.3	6.6	7.2	7.2
F^-	4.24	4.24	4.24	4.24
H_3BO_3	110.8	109.5	110.8	109.5
H_4SiO_4 (p)	187.3	200.3	186.6	197.7
H_4SiO_4 (к)	1048	1087	1160	1116
As	3.3	4.07	4.9	4.2
T Na/K, ^{0}C	275.1	275.4	274.8	277.1
T SiO_2, ^{0}C	254.1	259.7	265.8	258.7
T SiO_2(2), ^{0}C	278.8	282.5	289.3	285.3

2. CALCULATION OF HEAT CARRIER TEMPERATURE IN HYDROTHERMAL RESERVOIR BY GEOTHERMOMETERS

Data on concentration of silicic acid, cations of sodium Na^+, potassium K^+ and calcium Ca^{2+} in separate (Table 1a) were used to calculate temperature of liquid heat carrier in hydrothermal reservoir in productive zones of wells 048, 049 and 055. Calculations were done by equations for quartz (SiO_2)-geothermometer, and for sodium-potassium (Na-K) and sodium-potassium-calcium (Na-K-Ca)-geothermometers.

If temperature at which water-rock interaction occurs at a depth and type of rocks are known, then concentration of basic cations (Na^+, K^+) and anions

(Cl^-, SO_4^{2-}, HCO_3^-, CO_3^{2-}), ionic strength I_s, pH value at different temperature and pressure in heat equipment can be found from the condition of chemical equilibrium. Calculation of temperature by quartz SiO_2-geothermometer is based on the fact, that concentration of silica in water solution is determined by solubility of quartz at temperature of water-rock interaction (Fournier R.O., Rowe I.I. 1966). Thus, total content of silica is function of temperature. Different equations were suggested for approximation of this functional dependence which were obtained on the basis of mathematical processing of laboratory experimental data and data on measurements of temperature and silica concentrations in water solution of geothermal wells.

For SiO_2-geothermometer widely used are Fournier equation (Fournier R.O., Rowe I.I., 1966):
$$t_s = 1309/(5.19 - \lg C_t) - 273, (0-250^0C) \quad (2)$$
and Rimstidt equation:
$$\lg(C_t/60000) = 1.881 - 2.028 \cdot 0.001 \cdot (t_s + 273) - 1560/(t_s + 273), \quad (3)$$
where C_t – is total content of silica in solution expressed according to SiO_2, mg/kg, t_s–temperature of solution expressed in Celsius degrees, ^{0}C.

Na-K-geothermometers are based on the fact, that ratio of concentrations of sodium Na^+ and potassium K^+ cations in water solution is a function of temperature at which interaction of water with alkaline alumosilicate, for example, albite occurred. To calculate temperature by Na-K-geothermometers equation of White-Ellis is used (White D.E., 1965):

$$t_s = 855.6/(\lg(C_{Na}/C_K) + 0.8573) - 273, (0-245^0C) \quad (4)$$

Determination of temperature by Na-K geothermometer is also carried out by equation of Arnorsson (Arnorsson S., Gunalaugsson E., Svavarsson H., 1983):

$$t_s = 933/(\lg(C_{Na}/C_K) + 0.933) - 273, (25-250^0C) \quad (5)$$

In equations (4) and (5) C_{Na}, C_K – is concentration of sodium Na^+, potassium K^+ cations in solution, mg/l.

In some cases sodium-potassium-calcium (Na-K-Ca) geothermometer is used, which range of application is larger than that of sodium-potassium one. For this geothermometer additional ratio of concentrations of calcium Ca^{2+} cations and sodium Na^+ cations in water solution is used. We calculated temperature by Na-K-Ca-geothermometer on the basis of Fournier-Truesdell equation (Fournier R.O., Truesdell A., 1973):

$$t_s = 1647/(\lg(C_{Na}/C_K) + \beta_{CN} \cdot \lg((C_{Ca})^{0.5}/C_{Na}) + 2.24) - 273, (4 - 340^0C) \quad (6)$$

C_{Na}, C_K, C_{Ca}- are concentrations of sodium, potassium, calcium cations, correspondingly,

expressed in mole/l, β_{CN} – is coefficient which has the following values:

$$\beta_{CN}=1/3, \text{ if } (C_{Ca})^{0.5}/C_{Na}<1 \text{ и } t_s>100^0C, \qquad (7\text{-}1)$$

$$\beta_{CN}=4/3, \text{ if } (C_{Ca})^{0.5}/C_{Na}>1 \text{ и } t_s<100^0C \qquad (7\text{-}2)$$

Heat carrier of productive wells of Verkhne-Mutnovskaya geothermal electric power station has similar chemical composition, close vapour content and temperature. Therefore, temperature values calculated by named geothermometers should be considered as generalized characteristic of zone which is drained by wells.

Concentration of silica SiO_2 in separate sample (Table 1) was 643.8 mg/kg, concentration of cations Na^+ - 239.4 mg/l = $10.413 \cdot 10^{-3}$ mole/l, concentration of cations K^+ - 42.0 mg/l = $1.074 \cdot 10^{-3}$ mole/l, and concentration of cations Ca^{2+} - $0.0399 \cdot 10^{-3}$ mole/l. Substitution of these values into equations (2)-(7) gave the following results: temperature at the bottom hole according to Na-K-geothermometer (4) of White-Ellis - 269.3^0C, temperature according to Na-K-geothermometer of Arnorsson (5) - 257.4^0C, temperature according to Na-K-Ca-geothermometer of Fournier-Truesdell (6) - 249.1^0C.

Temperature calculated by geothermometer of Fournier-Truesdell should be considered as the lowest temperature limit within area of hydrothermal reservoir drained by productive wells of Verkhne-Mutnovskaya geothermal electric power station - $246\text{-}249^0C$. Temperature calculated by geothermometer of Arnorsson should be considered as the highest limit of values of real temperature in draining zone by the moment of sampling - $279\text{-}284^0C$.

For separate sample which chemical composition is shown in Table 1a at maximum possible temperature at the bottom hole of wells 279.4^0C concentration of silica SiO_2 before evaporation according to equation (3) was 519.1 mg/kg, and after evaporation - 643.8 mg/kg. Thus, minimal possible vapour content in heat carrier flow was 519.1/643.8 = 0.20.

3. MEASUREMENT OF RADII OF COLLOIDAL SILICA PARTICLES IN SEPARATE SAMPLES

When heat carrier comes up through the productive wells of geothermal electric power plant, then because of decrease in temperature and transformation of a part of heat carrier in vapour phase solution oversaturated relatively to solubility of amorphous silica comes to the surface. This leads to the development of nucleation and polymerization of orthosilicic acid molecules, in form of which silicium is mainly present in solution before coming to the surface. Formation of colloidal silica particles is the consequence of nucleation and polymerization. Flowing of separate through pipelines, heat equipment and reinjection wells is accompanied by the formation of complexes of silica particles on the walls of canals and growth of solid deposits layers.

The sizes and diffusion coefficients of colloidal silica particles which formed in hydrothermal solution during nucleation and polymerization were measured by the method of photon correlation spectroscopy (PCS). The experiments were done with photon correlation spectrometer of PhotoCor Complex class. Complete set of spectrometer includes optical block PhotoCor-Spec, correlator of PhotoCor-M class, laser and computer. He-Ne laser had capacity of 20 mW and wave length $\lambda_f = 633$ nm. Precision optical block of PhotoCor-Spec type contained precision goniometer which provided scattering angles $10^0\text{-}150^0$ and accuracy of turn up to 0.05^0, thermostat, photon counting system PhotoCor-Count, power supply unit PhotoCor-PMT-PS, optical bench, focusing unit for laser, adapters of dishes. Aliquots of solution were placed in square dishes of 12x12 mm.

Photon counting system PhotoCor-Count has highly effective receiving optical system. Signal from the outlet of photoreceiving block is analyzed by the one-plate multichannel correlator which is put directly in one of the joints of mother board of personal computer. By computer control for the process of measurement and processing of measurement results are carried out. Computer IBM PC compatible with monitor and printer is equipped with a set of special programs for PhotoCor systems of PhotoCor Soft-WIN type. Software allows to machine signals which entered into photon counting system, accumulate measurements of correlation function in different points, construct plots of correlation function. On the basis of the mathematical apparatus of theory of quasi-elastic scattering of monochromatic light on separate centers program calculates according to the values of correlation function time of correlation, diffusion coefficient of particles with definite size which participate in light scattering, determines concentration of particles with sizes in definite interval and calculate their average size.

Table 3 presents results of measurement in one of the samples of hydrothermal solution as dependence of amplitude of monochromatic laser light scattering with wave length 633.0 nm S_{am} on radius of particles R. Amplitude of scattering is proportional to quantity of particles with radii in corresponding value range. Mathematical processing of data on light scattering was done for particles having radii from 1.0 to 10000 nm. Average radius for particles of mentioned solution sample was 11.09 ± 0.18 nm, diffusion coefficient – 1.923 ± 0.03 cm^2/s (Table 3).

Investigations carried out by the method of photon correlation spectroscopy in hydrothermal solution samples showed, that the main fraction of particles had dimensions from 1.0 to 50.0 nm. Average radius of particles has values from 7.0 to 25.0 nm. Quantity of particles with dimensions more than 100.0 – 200.0 nm is relatively small.

Table 3. Results of measurements by the method of photon correlation spectroscopy in sample of hydrothermal separate of Verkhne-Mutnovsky geothermal electric power plant.

R, nm	S_{am}	R, nm	S_{am}
1.0 - 1.44	0.0222322	83.17 - 120.22	0.0270527
1.44 -2.089	0.0335038	120.226 - 173.78	0.0169228
2.0893 - 3.01995	0.0479776	173.78 - 251.189	0.00925547
3.019 - 4.365	0.0649203	251.189 - 363.078	0.00361224
4.365 - 6.309	0.0820874	363.078 - 524.807	0.0
6.309 - 9.12	0.0956918	524.807 – 758.578	0.0
9.12 -13.18	0.101794	758.578 – 1096.48	0.0
13.18 - 19.05	0.0986029	1096.48 – 1584.89	0.0
19.05 - 27.54	0.0875023	1584.89 - 2290.87	0.0
27.54 - 39.81	0.0718849	2290.87 – 3311.3	0.0
39.81 - 57.54	0.0552209	3311.3 – 4786.3	0.0
57.544 - 83.176	0.0398972	4786.3 – 10000.0	0.0

4. DETERMINATION OF SPECIFIC CONDUCTIVITY OF HYDROTHERMAL SOLUTIONS

Specific conductivity σ is another important characteristic of hydrothermal solution:

$$\sigma = \frac{h_{el}}{R_{el} \cdot S_{el}} \tag{8}$$

h_{el} – is a distance between electrodes, S_{el} – area of electrode plates, R_{el} – ohmic resistance of volume of solution in space between electrodes. According to the value of specific conductivity σ hydrothermal solution from Mutnovskoe field is referred to diluted electrolytes, according to the type of dependence of σ on temperature – to ion conductors (Potapov V.V., 2000). To calculate power imputs for electric treatment by formula it is necessary to know resistance of the electrocoagulator which is determined by the construction of electrocoagulator, strength and density of current and temperature on which conductivity of solution depends. Specific conductivity σ of multicomponent solution is estimated theoretically on the basis of equivalent conductivity λ_s, which is connected with σ value (Gerasimov Ya.I. et al., 1973):

$$\lambda_s = \sigma/c, \tag{9}$$

where c – is volume concentration of ion, mg·equiv/l. According to Kohlrausch's law (Gerasimov Ya.I. et al., 1973) with infinite dilution of electrolyte solution equivalent conductivity is equal to the sum of maximum ion mobilities u_i which are proportional to velocities of ion motion in electric field of E intensity and in approximation of Stock's regime flows of sphere of radius r_i are equal (Gerasimov Ya.I. et al., 1973):

$$u_i = \frac{z_i e}{6\pi r_i \mu} \cdot E \tag{10}$$

Using Kohlrausch's law we calculated theoretical value of specific conductivity σ for one of the samples of separate from well 014 of Mutnovskoe field. For 25^0C theoretical value is equal $\sigma = 1.571 \cdot 10^{-3}$ $Om^{-1} \cdot cm^{-1}$, that shows qualitative correspondence with experimental value for I = 1.5 A at 20^0C - $1.07 \cdot 10^{-3}$ $Om^{-1} \cdot cm^{-1}$. Na^+, K^+, Cl^-, HCO_3^-, SO_4^{2-}, CO_3^{2-} ions contribute to the largest extent to the value of specific conductivity of multicomponent solution. Total contribution of these ions to specific conductivity was 97.92%. Values of maximum ion mobility in water at temperature of 25^0C, their concentrations and relative contribution to specific conductivity of hydrothermal solution are given in Table 4.

Table 4. Maximum ion mobilities in hydrothermal solution at 25 ^0C and relative contribution to specific conductivity of solution.

Ion	Maximum mobility, cm²/Om· g·equiv	Ion concentration, mg·equiv/dm³	Relative contribution to specific conductivity, %
H_3O^{3+}	349.8	$10^{-5.9}$	0.00002
Li^+	38.6	0.1873	0.46
Na^+	50.1	10.43	33.24
K^+	73.5	1.46	6.82
NH_4^+	73.5	0.04	0.187
Mg^{2+}	53.0	0.0197	0.066
Ca^{2+}	59.5	0.2	0.757
Al^{3+}	63.0	0.0309	0.123
Fe^{2+}	53.5	0.0107	0.036
Fe^{3+}	68.0	0.0161	0.0697
OH^-	197.6	0.00606	0.083
F^-	55.4	0.08	0.281
Cl^-	76.4	8.20	39.85
HCO_3^-	44.5	0.72	2.039
SO_4^{2-}	80.0	2.60	13.23
CO_3^{2-}	69.3	0.62	2.73

Table 5a. Ohmic resistance of electrocoagulator and conductivity of solution depending on the temperature (I = 1.5A, j = 112.7 A/m², h_{el} = 10 mm).

t_s, ^0C	55.0	43.0	36.0	30.0	27.0	23.0	20.0
$\sigma \cdot 10^3$, (Om·cm)$^{-1}$	1.73	1.50	1.41	1.33	1.25	1.18	1.07

Table 5b. Specific conductivity of separate solution from Verkhne-Mutnovsky geothermal electric power plant depending on the temperature (I = 1.0 A, j = 86.95 A/m^2, h_{el} = 10 mm).

t_s,^{0}C	$\sigma \cdot 10^3$, (Om·cm)$^{-1}$	$\sigma_{theor} \cdot 10^3$, (Om·cm)$^{-1}$	$\mu \cdot 10^3$, Pa·s	$\alpha=\sigma/\sigma_{theor}$
130	3.85	6.200	0.211	0.620
128	3.64	6.113	0.214	0.595
123	3.50	5.866	0.223	0.596
117	3.32	5.543	0.236	0.598
109	3.05	5.150	0.254	0.592
99	2.92	4.655	0.281	0.627
89	2.78	4.166	0.314	0.667
76	2.38	3.545	0.369	0.671
63	2.01	2.959	0.442	0.679
50	1.76	2.404	0.544	0.732
36	1.45	1.858	0.704	0.780
20	1.28	1.307	1.001	0.979

To reveal dependence of resistance R_{el} upon temperature experiments were carried out on treatment of separate from well 014 at strength of current I = 1.5 A and current density j = 112.7 A/m^2 in a range t_s = 20-60^{0}C. Measurement results for specific conductivity of hydrothermal solution within temperature range 20-60^0 C are given in Table 5a. Table 5b presents experimental data on measurement of σ value in separate solution from Verkhne-Mutnovsky geothermal electric power plant within a range of 20-130^0 C.

According to the data from Table 5a, resistance of electrocoagulator with solution of hydrothermal separate decreased with increase in temperature: value R_{el} decreased 1.6 times with increase in temperature from 20 to 60^{0}C. Specific conductivity σ increased 1.6 times with increase in temperature from 20 to 60^{0}C. Growth in specific conductivity corresponded to the fact, that according to equation (10) with increase in temperature and decrease in viscosity of water μ mobilities of u_i ions of solution increase, that leads to the growth in equivalent λ_s and specific σ conductivities.

Equation (10) shows, that mobility of separate ions and, therefore, specific conductivity of solution, are inversely proportional to dynamic viscosity of solution. Table 5b gives values of viscosity at different temperature, calculated by equation (Vukalovich M.P., Rivkin S.L., Aleksandrov A.A., 1969):

$$\mu(t_s) = 0.0000001 \cdot 241.4 \cdot 10^{247.8/(t_s - 140)} \qquad (11)$$

Taking into account dependence of viscosity upon temperature according to equation (10), theoretical values σ_{theor} of specific conductivity were calculated (see the last column in Table 5b). At 20 ^{0}C theoretical value σ_{theor} slightly differs from the experimental one (Table 5b). At higher temperatures 50-130 ^{0}C this difference is more substantial: theoretical values are 1.4-1.69 times large than experimental ones. Thus, equations (9), (10) and (11) make it possible to estimate value σ at different ion concentrations, pH, temperature of solution by introducing the coefficient $\alpha=\sigma/\sigma_{theor}$ values of which are within 0.73-0.59 at higher temperature.

Table 6. Concentrations of anions and cations in hydrothermal separate of well 103 of Pausgetskoe field. I_s=52.401 mmol/kg, σ=5.03·10^{-3} (Om·cm)$^{-1}$ (18.4 ^{0}C), n.d.-concentration was not determined, (-)-values were not calculated.

Component	mg/l	mg·equiv/l		Relative contribution to specific conductivity, %
		mg·equiv/l	mg·equiv/l %	
Na$^+$	877.5	38.15	86.1	33.54
K$^+$	98.9	2.54	5.7	3.27
Ca^{2+}	54.08	2.7	6.1	2.819
Mg^{2+}	<1.2	-	-	-
Fe$^{2,+}$	<0.1	-	-	-
Fe^{3+}	<0.3	-	-	-
Al^{3+}	n.d.	-	-	-
NH$_4^+$	1.0	0.06	0.1	0.077
Li$^+$	6.1	0.88	2.0	0.596
Sum of cations	1037.58	44.33	100.0	40.30
Cl$^-$	1418.4	40.0	91.1	53.639
HCO$_3^-$	44.82	0.73	1.7	0.57
CO$_3^{2-}$	0.45	0.02	0.0	0.024
SO$_4^{2-}$	134.48	2.8	6.4	3.931
H$_3$SiO$_4^-$	3.98	0.04	0.1	-
H$_2$BO$_3^-$	14.51	0.24	0.6	-
F$^-$	1.56	0.082	0.19	1.516
Sum of anions	1618.2	43.91	100.0	59.68
H$_3$BO$_3$	207.02	-	-	-
(H$_4$SiO$_4$)$_t$	512.0	-	-	-
Mineralization	3458	-	-	-
pH	8.03	-	-	-

In the table 6 data on the concentrations of cations and anoins in hydrothermal separate of well 103 of Pausgetskoe field are presented. Experimental value of specifhic conductivity of separate at 18.4 ^{0}C was σ=5.03·10^{-3} (Om·cm)$^{-1}$, theoretical value calculated from the equations (9), (10), (11) was σ=5.697·10^{-3} (Om·cm)$^{-1}$ at 25^{0}C and σ=4.869·10^{-3} (Om·cm)$^{-1}$ at 18.4^{0}C, so value $\alpha=\sigma/\sigma_{theor=}$ at 18.4^{0}C was 1.033. Thus, one can use these equations for prediction of

separate speciphic conductivity at different hydrothermal of parameters of hydrothermal solution: temperature, ions concentrations, pH, ionic strength.

CONCLUSIONS

1. According to concentrations of silica, sodium and potassium in separate solution from wells of Mutnovskoe field temperature of heat carrier in drained zone of hydrothermal reservoir is within a range from 250 to 300^0C. In solution of separate ions of sodium and potassium have the largest concentration among cations, chlorine-ion and sulphate-ion - among anions. Separate is referred to chloride-sulphate-sodium-potassium type of hydrothermal solutions.

2. Processes of nucleation and polymerization of orthosilicic acid in oversaturated solution of separate lead to the formation of colloidal silica particles average radii of which are within a range from 1.0 to 20.0 nm. The main fraction of particles has radii in a range from 1.0 to 50.0 nm.

3. Experimental values of specific conductivity of separate at different temperature are in quantitative correspondence with theoretical values calculated on the basis of Kohlrausch's law, of maximum values of ion mobility and viscosity of water. It makes it possible to forecast conductivity of hydrothermal solution at different temperature, ions concentrations, pH, ionic strength of solution and estimation of consumption of electric power for silica precipitation by electrocoagulation.

4. We revealed physical and chemical characteristics of hydrothermal separate which are important for solving the problem of solid deposits and for the development of silica precipitation technology: 1) total content C_t of silica in solution; 2) average radius, area of surface of colloid silica particles; 3) concentration of basic cations (Na^+, K^+) and anions (Cl^-, SO_4^{2-}); 4) pH; 5) mineralization of solution M_h; 6) ionic strength I_s; 7) specific conductivity of solution σ.

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