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THERMODYNAMICS OF CARBOTHERMAL REDUCTION PROCESS COPPER SLAG

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ABSTRACT

The article analyses the thermodynamic laws of processing iron-based compounds contained in copper production slag using the method of carbothermic recovery. Evaluation of the probable direction of carbothermic reactions occurring between oxidized compounds and carbon in the slag was carried out by changing the thermodynamic values of the system. In the thermodynamic scientific justification of the physic-chemical processes occurring in the carbothermic recovery of metal oxides in slag, the change of Gibbs energy of the system with temperature increases and the estimation of equilibrium constants of chemical reactions based on Gibbs energy and the method of determining the slowest (limiting) chemical process among them were used. The Microsoft Excel program was used to determine the thermodynamic values of the chemical reactions occurring in the slag and reducing agent system and to compile their Ellingham graphs.

Keywords: *carbothermal reduction, thermodynamics, copper slag, Gibbs free energy, physic-chemical processes.*

INTRODUCTION

The rapid development of the metallurgical industry on a global scale, along with the creation of new types of metals and metal alloys, creates various metallurgical wastes [1].

To process the generated waste, developed countries should implement complex processing technology, regulate their regulatory documents for the development of the industry, create a system of environmental laws, support "green technologies", as well as solve the technological tasks of manufacturers. The advanced and low-waste technologies involved in the development are the involvement [2].

Processing of metallurgical slags, obtaining new types of products and applying the residual product to the construction material production industry is one of the most urgent tasks of today.

One of the most optimal technologies for processing copper slag is processing in a reducing environment containing carbon [3 - 5].

EXPERIMENTAL

The most important aspect in processing with carbonaceous regenerates is its thermodynamic analysis. Thermodynamic analyses were carried out taking into account the dependence of isobaric-isothermal potentials (Gibbs free energy) on temperature. The Gibbs free energy change (ΔG) is generally calculated using the following formula:

$\Delta G_{reac} = \Delta H_{reac} - \Delta S_{reac} T$

where ΔH_{reak} is the enthalpy of the corresponding chemical reaction, kJ mol^{-1}, ΔS_{reak} - the entropy, J $mol^{-1}K^{-1}$, T - the absolute temperature of the system, K.

Depending on the value of the Gibbs energy of the system, it is concluded as follows about whether the reactions will proceed or not and the direction of the reaction under standard conditions:

a) if the Gibbs energy change value $\Delta G_{298} > 0$, these reactions cannot proceed spontaneously under standard conditions;

b) if $\Delta G_{298} < 0$, these reactions proceed spontaneously under standard conditions. These reactions are economically and technologically favourable;

d) if $\Delta G_{298} = 0$, then the system is in a state of chemical equilibrium. It is necessary to change the parameters of the system (p, T, c, V) to direct the equilibrium in the direction of the desired reaction [6].

The standard thermodynamic values of the substances involved in the chemical reactions occurring in the slag and reducing agent system were determined from the appendix given in the literature [7], and these standard values are presented in Table 1. of the reaction equilibrium constant (K_M) was determined by the following formula:

$\Delta G = - RT \ln K_M$

where R is the universal gas constant, $R = 8.31696 \times 10^{-3}$ kJ mol^{-1}K^{-1}.

To find the equilibrium constant from the above formulae, we divide both sides of the equation by - RT and logarithm, and as a result, the following expression is formed:

$$K_M = e^{-\frac{\Delta G}{RT}}$$

For each of the reduction reactions with carbon, the change in Gibbs energy at the initially given temperature was expressed by a general formula.

Oxidation-reduction reactions can proceed with different mechanisms both in heterogeneous phases and inhomogeneous phases. In most cases, the initial stage of the reaction occurs with the transfer of electrons at the reaction interface. Oxidation usually occurs in regions with the highest electron density, while reduction occurs in regions with the lowest electron density. Due to the high relative electronegativity of oxygen in the oxides of the slag, the valence electrons in the outer layer of the metal atoms move to the side of the oxygen atoms. As a result, the electron density is higher on the oxygen side, creating a negative polarity. Due to valence electrons leaving metal atoms, there is an imbalance between the number of electrons corresponding to the number of protons in the atomic nucleus. Since the number of electrons in the orbital of a metal atom is less than the number of protons in its nucleus, this metal atom has a positive pole. As a result, the electron density in the region of metal atoms decreases [7].

According to the mechanism of carbothermic reactions, the activation energy of carbon and solid slag materials is initially given at the contact boundary, and the internal energy of each component in the system increases, forcing it to perform certain work. In this case, the degree of disorder in the particles of the reducing agent and oxide compounds increases (that is, the entropy increases), and the electrons in the neutral

Table 1. Thermodynamic values of substances under standard conditions (298 K).

Substance	ΔH_{298}, kJ mol^{-1}	ΔG_{298}, kJ mol^{-1}	ΔS_{298}, J mol^{-1}K^{-1}
Cu_2O	- 173.2	- 150.6	92.9
FeO	-265	-244	60.8
Fe_2SiO_4	-1477.8	-1377.0	145.2
CO	-110.52	-137.14	197.54
CO_2	-393.51	-394.38	213.67
CaO	-635.1	-603.1	38.1
Ca_2SiO_4	-2307.5	-2192.8	127.74
SiO_2	-905.4	-851.6	43.51
Cu	0	0	33.1
Fe	0	0	27.15
C	0	0	5.74

carbon atom begin to twist toward the metal ions with relatively positive polarity (or a positive oxidation state) according to the laws of electrostatic attraction. As a result, on the reactive surface of the oxide layer, the electrons in the carbon atom begin to be adsorbed and an electric double layer is formed, which can exist only for a few fractions of a second. At the next stage of the carbothermic recovery mechanism, the positive metal atom receives the electrons given by carbon and goes to a neutral state. The carbon atom itself, which has given its electrons, has a positive oxidation state and binds with oxygen, which has a negative oxidation state [4]. The electronic balance of oxidation-reduction reactions occurring during the reduction of divalent metal oxide with carbon can be written as follows:

$C^0 - 2e^- \rightarrow C^{+2}$ (oxidation)
$Me^{+2} + 2e^- \rightarrow Me^0$ (recovery)
Me is Fe and Cu metals.

The reaction products formed in the next stage of carbothermic recovery leave the reaction zone. In this case, oxidized carbon atoms combine with oxygen to form carbon dioxide (CO) and leave the reaction surface due to the high entropy and low density of this gas:

$CO_{(adsorption)} \rightarrow CO_{(desorption)}\uparrow$

At the next stage of the carbothermic recovery process, carbon dioxide molecules, while moving through the capillary cracks in the raw materials, interact with metal oxides that have not yet been recovered due to the presence of reductive properties and are oxidized to carbon dioxide (CO_2). In this process, carbon dioxide molecules are initially chemisorbed on the surface of metal oxides, then completely leave the reaction zone in the form of CO_2. In general, the electronic balance of the heat recovery process can be imagined as follows:

$C^{+2} - 2e^- \rightarrow C^{+4}$ (oxidation)
$Me^{+2} + 2e^- \rightarrow Me^0$ (recovery)

Depending on the speed of the chemical reactions that take place in the carbothermic recovery process, it is possible to establish the sequence of which reaction will proceed in the system first and which reaction will follow it. For this, it is necessary to determine the change of their free energy in the range of several temperatures and the equilibrium constants at these temperatures. For this reason, in order to perform thermodynamic analysis in an easy and understandable language, based on the reaction mechanism established above, all carbothermic recovery chemical reactions that occur in the process of obtaining metal by reducing metal oxides in copper production slag with carbon were studied into 2 groups: 1) reduction of oxides initially with carbon (C); 2) reduction of oxides with carbon dioxide (CO) [5].

RESULTS AND DISCUSSION

Thermodynamic analysis of carbon reduction of metal oxides in slag

The carbothermic recovery reactions between the slag and the carbon were constructed and they are as follows**:**

$Cu_2O + C = 2Cu + CO\uparrow$ (1)
$FeO + C = Fe + CO\uparrow$ (2)
$Fe_2SiO_4 + 2C = 2Fe + SiO_2 + 2CO\uparrow$ (3)
$Fe_2SiO_4 + 2CaO + 2C = 2Fe + Ca_2SiO_4 + 2CO\uparrow$ (4)

Using the values given in Table 1, the results of Hess's law of reduction chemical reactions with carbon under standard conditions were calculated and are presented in Table 2.

From the values of thermodynamic calculations presented in Table 2 under standard conditions, all chemical reactions are endothermic reactions, and their standard Gibbs energy values are positive, that is, at 298 K, the reaction cannot occur spontaneously. A certain amount of heat absorption was observed in all carbothermic chemical reactions. Although heat is absorbed ($\Delta H_{reak} > 0$), but the entropy of the system has

Table 2. Values of carbothermic recovery reactions under standard conditions (298 K).

No	Chemical reactions	ΔH_{reac}, kJ	ΔG_{reac}, kJ	ΔS_{reac}, J K^{-1}
1	$Cu_2O + C = 2Cu + CO\uparrow$	62.68	13.46	165.1
2	$FeO + C = Fe + CO\uparrow$	154.48	106.86	158.15
3	$Fe_2SiO_4 + 2C = 2Fe + SiO_2 + 2CO\uparrow$	351.36	251.12	336.21
4	$Fe_2SiO_4 + 2CaO + 2C = 2Fe + Ca_2SiO_4 + 2CO\uparrow$	219.46	116.12	344.24

increased due to the formation of gases in the reaction ($\Delta S_{reak} > 0$). The increase of entropy in the particles formed in the system of carbothermic reactions under investigation increases the diffusion of the gases formed and prepares a favourable ground for the next stage of recovery.

To visualize the contribution of each chemical reaction in the study of enthalpy and entropy in a reaction, they are depicted in the form of a pie chart in Fig. 1.

From the diagram of the circle described in Fig. 1, the largest amount of heat is absorbed in chemical reaction 3. For this reason, the temperature of this reaction is much higher. And in Fig. 1b, as a result of the 4th chemical reaction, the level of particle disturbance in the reaction system increases sharply.

Based on the conclusions of Table 2, the corresponding mathematical expressions of the relationship between how the temperature rise affects the response of each reduction are created, and they are as follows:

1	$Cu_2O + C = 2Cu + CO\uparrow$	$\Delta G_1^T = 62.68 - 0.1651\ T$
2	$FeO + C = Fe + CO\uparrow$	$\Delta G_2^T = 154.48 - 0.15815\ T$
3	$Fe_2SiO_4 + 2C = 2Fe + SiO_2 + 2CO\uparrow$	$\Delta G_3^T = 351.36 - 0.33621\ T$
4	$Fe_2SiO_4 + 2CaO + 2C = 2Fe + Ca_2SiO_4 + 2CO\uparrow$	$\Delta G_4^T = 219.46 - 0.34424\ T$

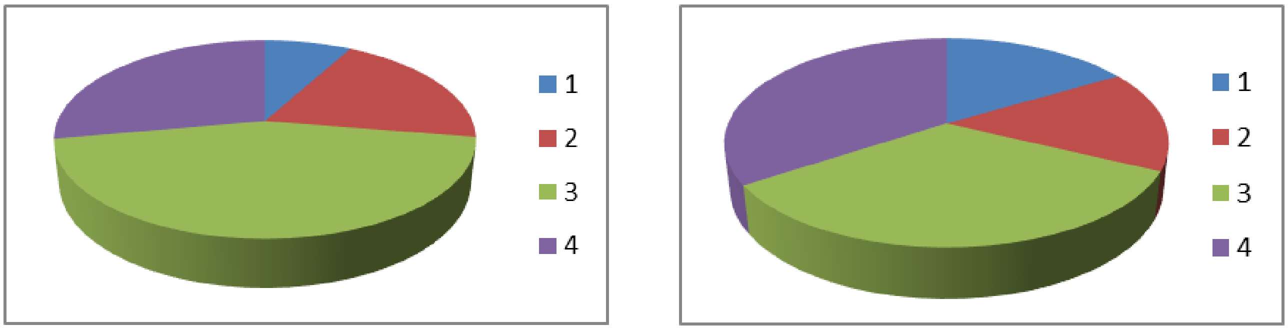

Fig. 1. Reflection of enthalpy and entropy values of renewable reactions involving carbon in fractions: a) contribution of reducing reactions when heating heat; b) contribution of each reaction during entropy of the system after the reduction reaction.

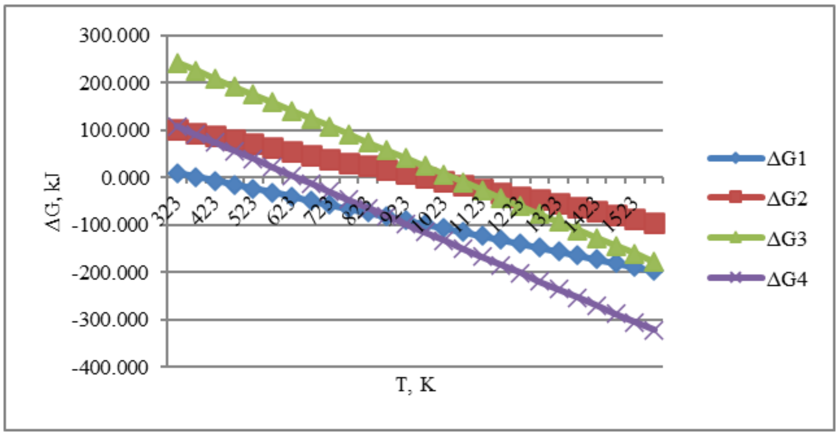

Fig. 2. General Ellingham diagram of reduction reactions occurring in the oxide-carbon system.

Table 3. Values of Gibbs energies of reduction reactions in the presence of carbon at different temperatures.

No	T, K	ΔG_1^T, kJ	ΔG_2^T, kJ	ΔG_3^T, kJ	ΔG_4^T, kJ
1	323	9.353	103.398	242.764	108.270
2	373	1.098	95.490	225.954	91.058
3	423	-7.157	87.583	209.143	73.846
4	473	-15.412	79.675	192.333	56.634
5	523	-23.667	71.768	175.522	39.422
6	573	-31.922	63.860	158.712	22.210
7	623	-40.177	55.953	141.901	4.998
8	673	-48.432	48.045	125.091	-12.214
9	723	-56.687	40.138	108.280	-29.426
10	773	-64.942	32.230	91.470	-46.638
11	823	-73.197	24.323	74.659	-63.850
12	873	-81.452	16.415	57.849	-81.062
13	923	-89.707	8.508	41.038	-98.274
14	973	-97.962	0.600	24.228	-115.486
15	1023	-106.217	-7.307	7.417	-132.698
16	1073	-114.472	-15.215	-9.393	-149.910
17	1123	-122.727	-23.122	-26.204	-167.122
18	1173	-130.982	-31.030	-43.014	-184.334
19	1223	-139.237	-38.937	-59.825	-201.546
20	1273	-147.492	-46.845	-76.635	-218.758
21	1323	-155.747	-54.752	-93.446	-235.970
22	1373	-164.002	-62.660	-110.256	-253.182
23	1423	-172.257	-70.567	-127.067	-270.394
24	1473	-180.512	-78.475	-143.877	-287.606
25	1523	-188.767	-86.382	-160.688	-304.818
26	1573	-197.022	-94.290	-177.498	-322.030

Based on the calculated mathematical expressions, the probability of occurrence of each recovery chemical process was determined when the temperature in the reaction system increases by 50 units. The obtained results are presented in Table 3.

Table 3 presents the corresponding Gibbs energies of reduction chemical reactions in the presence of carbon in the temperature range of 323 - 1573K, and the probability of occurrence of all endothermic reactions increased with increasing temperature. For example, in the reduction reaction of copper lower oxide (reaction 1), the Gibbs energy is at a temperature of 423 K, in the reduction reaction of iron lower oxide (reaction 2), the Gibbs energy is at a temperature of 1023 K, in the recovery of fayalite (reaction 3) Gibbs energy at 1073 K , in the recovery of fayalite in the presence of lime (reaction 4), the Gibbs energy becomes negative at 673 K, that is, the recovery reactions of metal oxides in the slag are budded at the same temperatures father starts This can also be clearly seen in Fig. 2.

In the graph shown in Fig. 2, among the chemical reactions of recovery in the oxide and carbon system, the fastest chemical reactions are reactions 1 and 4. When the temperature in the reaction system reaches 873 K, the rates of these two chemical reactions become equal, and when the temperature increased another 50 units

Table 4. Values of equilibrium constants of reduction reactions involving carbon at different temperatures.

No	T, K	K_1	K_2	K_3	K_4
1	323	0.9965	0.9622	0.9135	0.9605
2	373	0.9996	0.9697	0.9297	0.9711
3	423	1.0020	0.9754	0.9422	0.9792
4	473	1.0039	0.9799	0.9522	0.9857
5	523	1.0055	0.9836	0.9604	0.9910
6	573	1.0067	0.9867	0.9672	0.9953
7	623	1.0078	0.9893	0.9730	0.9990
8	673	1.0087	0.9914	0.9779	1.0022
9	723	1.0095	0.9933	0.9821	1.0049
10	773	1.0102	0.9950	0.9859	1.0073
11	823	1.0108	0.9964	0.9891	1.0094
12	873	1.0113	0.9977	0.9921	1.0112
13	923	1.0118	0.9989	0.9947	1.0129
14	973	1.0122	0.9999	0.9970	1.0144
15	1023	1.0126	1.0009	0.9991	1.0157
16	1073	1.0129	1.0017	1.0011	1.0170
17	1123	1.0132	1.0025	1.0028	1.0181
18	1173	1.0135	1.0032	1.0044	1.0191
19	1223	1.0138	1.0038	1.0059	1.0200
20	1273	1.0140	1.0044	1.0073	1.0209
21	1323	1.0143	1.0050	1.0085	1.0217
22	1373	1.0145	1.0055	1.0097	1.0224
23	1423	1.0147	1.0060	1.0108	1.0231
24	1473	1.0149	1.0064	1.0118	1.0238
25	1523	1.0150	1.0068	1.0128	1.0244
26	1573	1.0152	1.0072	1.0137	1.0249

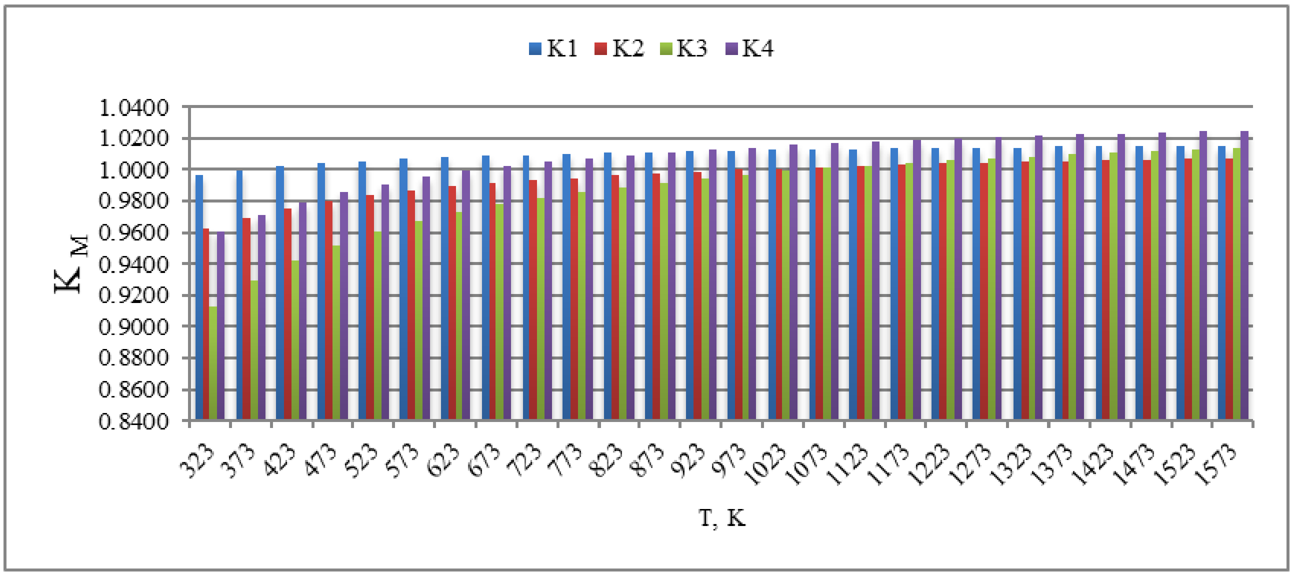

Fig. 3. Variation of the equilibrium constant during the reduction of oxides with carbon depending on the temperature.

(that is, when it reached 923 K), reaction 4 outpaced all other chemical reactions.

Based on the mathematical expression and the values of free energies in Table 3, the chemical equilibrium constants at given temperatures for each reduction reaction involving carbon were determined and these values are presented in Table 4.

From the values in Table 4 and these values in the form of histograms in Fig. 3, it can be understood that when the temperature reaches 1573 K, the equilibrium constant of the recovery of reaction 4, that is, with the participation of activated lime (CaO), reaches its maximum value (K_M = 1.0249).

The slowest (limiting) process among the chemical reactions that take place during the recovery of oxides contained in copper production slag in the presence of carbon is the recovery of fayalite (reaction 3).

Since the reduction reaction of fayalite in the presence of carbon is endothermic, increasing the temperature increases the reaction rate. However, because the addition of lime (CaO) to the system binds SiO_2 formed from the recovery of fayalite, it was concluded that it is appropriate and economically important to organize the recovery process with the participation of lime, and the temperature of 1573 K the general was chosen as the optimum temperature for carbothermic reactions.

3.2. Thermodynamic analysis of the recovery process of metal oxides in slag with carbon dioxide (CO)**.** The carbothermic recovery reactions between liquid slag and flue gas are as follows:

$$Cu_2O + CO = 2Cu + CO_2\uparrow \quad (5)$$
$$FeO + CO = Fe + CO_2\uparrow \quad (6)$$
$$Fe_2SiO_4 + 2CO = 2Fe + SiO_2 + 2CO_2\uparrow \quad (7)$$
$$Fe_2SiO_4 + 2CaO + 2CO = 2Fe + Ca_2SiO_4 + 2CO_2\uparrow \quad (8)$$

Using the values given in Table 1, the results of the recovery chemical reactions between the components of silicate slag according to Hess's law were calculated under standard conditions and are presented in Table 5.

From the values of thermodynamic calculations presented in Table 5 under standard conditions, the 5th, 6th and 8th chemical reactions are exothermic reactions, their standard Gibbs energy values are negative, that is, the reaction occurs spontaneously at 298 K will be only in the 7th chemical reaction, a certain amount of heat absorption was observed. Although most carbothermic reactions are exothermic ($\Delta H_{reak} < 0$), the entropy of the system decreases because of the reaction ($\Delta S_{reac} < 0$).

From the values presented in Table 5, the corresponding mathematical expressions of the relationship between how the temperature increase in the reaction system affects each recovery reaction were constructed, and they look like this:

1 $Cu_2O + CO = 2Cu + CO_2\uparrow$ $\Delta G_5^T = -109.79 + 0.01057\ T$
2 $FeO + CO = Fe + CO_2\uparrow$ $\Delta G_6^T = -17.99 + 0.01752\ T$
3 $Fe_2SiO_4 + 2CO = 2Fe + SiO_2 + 2CO_2\uparrow$ $\Delta G_7^T = 6.42 + 0.01513\ T$
4 $Fe_2SiO_4 + 2CaO + 2CO = 2Fe + Ca_2SiO_4 + 2CO_2\uparrow$ $\Delta G_8^T = -125.48 + 0.0071\ T$

Table 5. Values of reduction reactions with Is gas under standard conditions (298 K).

No	Chemical reactions	ΔH_{reac}, kJ	ΔG_{reac}, kJ	ΔS_{reac}, J K^{-1}
1	$Cu_2O + CO = 2Cu + CO_2\uparrow$	-109.79	-106.64	-10.57
2	$FeO + CO = Fe + CO_2\uparrow$	-17.99	-13.24	-17.52
3	$Fe_2SiO_4 + 2CO = 2Fe + SiO_2 + 2CO_2\uparrow$	6.42	10.92	-15.13
4	$Fe_2SiO_4 + 2CaO + 2CO = 2Fe + Ca_2SiO_4 + 2CO_2\uparrow$	-125.48	-124.08	-7.1

Based on the calculated mathematical expressions, the probability of occurrence of each recovery chemical process was determined when the temperature in the reaction system increases by 50 units. The obtained results are presented in Table 6.

Table 6 presents the corresponding Gibbs energies of chemical reduction reactions in the presence of carbon dioxide in the temperature range of 323 - 1573 K. Gibbs energy values in all reduction reactions became positive with increasing temperature. Even though it is an exothermic process, chemical reaction 5, i.e. reduction of copper oxide with carbon dioxide, and reaction 8, i.e.

reduction of fayalite with carbon dioxide in the presence of calcium oxide, are more likely to occur in the given temperature range. But the 7th chemical reaction, i.e., the recovery of the activity itself with carbon dioxide, is unlikely to occur at all given temperature values. The recovery of the 6th chemical reaction, that is, wustite with carbon dioxide, occurs with a very low probability at initial temperatures. Unfortunately, temperatures above 1073 K stop wustite from recovering. This can also be clearly seen in Fig. 4.

In the graph shown in Fig. 4, among the recovery chemical reactions in the system of metal oxide and carbon dioxide, the fastest chemical reaction is reaction 8, i.e. recovery of fayalite with carbon dioxide in the presence of lime. After that, reduction of copper oxide with carbon dioxide is considered. Other reactions are very unlikely or non-existent in practice.

Based on the mathematical expression and the values of Gibbs energies in Table 6, the chemical equilibrium constants at the given temperatures for each reduction reaction in the presence of is gas were determined, and these values are presented in Table 7.

Fig. 5 shows the values of the chemical equilibrium constants of the reactions of metal oxides contained in copper production slags with carbon dioxide in the temperature range, and the values of the equilibrium constants of the recovery reactions decrease with the increase in temperature. But the equilibrium constant of the 5th and 8th chemical reactions is greater than one even at the maximum temperature values ($K_M > 1$). In this case, although the speed of these chemical reactions decreases slightly with the increase in temperature, reaction products continue to be formed. Since the equilibrium constants of chemical reactions

Table 6. Values of Gibbs energy at different temperatures of reduction reactions in the presence of heat gas.

No	T, K	ΔG_5^T, kJ	ΔG_6^T, kJ	ΔG_7^T, kJ	ΔG_8^T, kJ
1	323	-106.376	-12.331	11.307	-123.187
2	373	-105.847	-11.455	12.063	-122.832
3	423	-105.319	-10.579	12.820	-122.477
4	473	-104.790	-9.703	13.576	-122.122
5	523	-104.262	-8.827	14.333	-121.767
6	573	-103.733	-7.951	15.089	-121.412
7	623	-103.205	-7.075	15.846	-121.057
8	673	-102.676	-6.199	16.602	-120.702
9	723	-102.148	-5.323	17.359	-120.347
10	773	-101.619	-4.447	18.115	-119.992
11	823	-101.091	-3.571	18.872	-119.637
12	873	-100.562	-2.695	19.628	-119.282
13	923	-100.034	-1.819	20.385	-118.927
14	973	-99.505	-0.943	21.141	-118.572
15	1023	-98.977	-0.067	21.898	-118.217
16	1073	-98.448	0.809	22.654	-117.862
17	1123	-97.920	1.685	23.411	-117.507
18	1173	-97.391	2.561	24.167	-117.152
19	1223	-96.863	3.437	24.924	-116.797
20	1273	-96.334	4.313	25.680	-116.442
21	1323	-95.806	5.189	26.437	-116.087
22	1373	-95.277	6.065	27.193	-115.732
23	1423	-94.749	6.941	27.950	-115.377
24	1473	-94.220	7.817	28.706	-115.022
25	1523	-93.692	8.693	29.463	-114.667
26	1573	-93.163	9.569	30.219	-114.312

6 and 7 are less than one, the slowest (i.e., limiting) reaction in the general recovery process is the reduction of copper oxide with carbon dioxide (reaction 5). Therefore, the fastest temperature of the 5th chemical reaction (i.e., 323 K) was chosen when determining the optimal temperature in the recovery process with hot gas. At this temperature, the rate of chemical reaction 8 is also much higher.

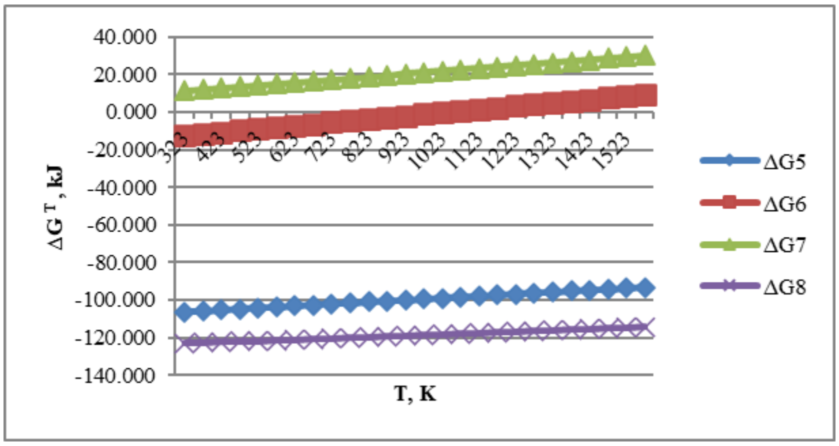

Fig. 4. General Ellingham diagram of the reduction reactions taking place in the metal oxide and carbon dioxide system.

Table 7. Values of equilibrium constants of reduction reactions in the presence of hot gas at different temperatures.

No	T, K	K_5	K_6	K_7	K_8
1	323	1.0404	1.0046	0.9958	1.0470
2	373	1.0347	1.0037	0.9961	1.0404
3	423	1.0304	1.0030	0.9964	1.0355
4	473	1.0270	1.0025	0.9966	1.0316
5	523	1.0243	1.0020	0.9967	1.0284
6	573	1.0220	1.0017	0.9968	1.0258
7	623	1.0201	1.0014	0.9969	1.0237
8	673	1.0185	1.0011	0.9970	1.0218
9	723	1.0171	1.0009	0.9971	1.0202
10	773	1.0159	1.0007	0.9972	1.0189
11	823	1.0149	1.0005	0.9972	1.0176
12	873	1.0140	1.0004	0.9973	1.0166
13	923	1.0131	1.0002	0.9973	1.0156
14	973	1.0124	1.0001	0.9974	1.0148
15	1023	1.0117	1.0000	0.9974	1.0140
16	1073	1.0111	0.9999	0.9975	1.0133
17	1123	1.0105	0.9998	0.9975	1.0127
18	1173	1.0100	0.9997	0.9975	1.0121
19	1223	1.0096	0.9997	0.9976	1.0116
20	1273	1.0091	0.9996	0.9976	1.0111
21	1323	1.0088	0.9995	0.9976	1.0106
22	1373	1.0084	0.9995	0.9976	1.0102
23	1423	1.0080	0.9994	0.9976	1.0098
24	1473	1.0077	0.9994	0.9977	1.0094
25	1523	1.0074	0.9993	0.9977	1.0091
26	1573	1.0072	0.9993	0.9977	1.0088

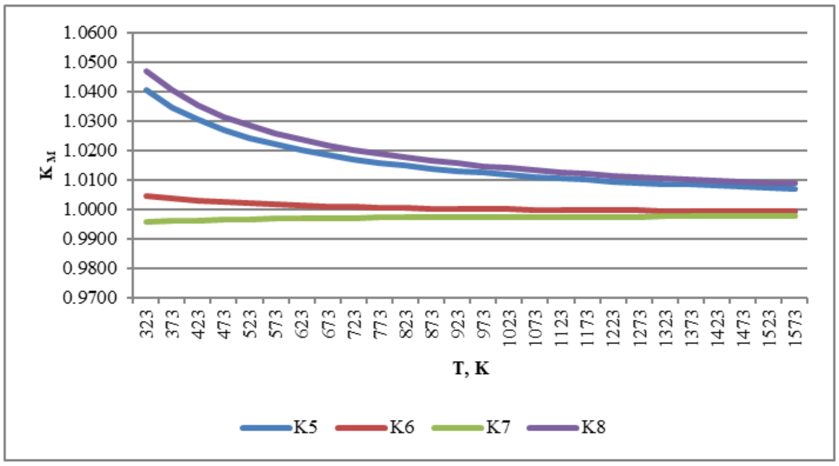

Fig. 5. Variation of the equilibrium constant in the process of recovery of metal oxides with hot gas depending on the temperature.

CONCLUSIONS

Having determined that all reactions in the process of low temperature carbonothermic recovery of iron oxide compounds contained in steel and copper production slags using coal proceed in an endothermic state, the results of recovery reactions between carbon and slag components under standard conditions were developed according to Hess's law. As a result, iron-containing compounds in steel and copper production slags are restored with the help of carbon, increasing the level of metallization and allowing to separate them from the process by the property of magnetism.

By keeping the optimal temperature in the range of 1050 - 1100^{0}C, the level of metallization was increased to 89 % by calculating the equilibrium logarithmic constants of the reactions of reducing oxides contained in coal sands in the reducing medium. As a result, the costs for the restoration of iron-based compounds can be reduced by 34 %.

A reaction system of recovery chemical reactions flowing in the oxide-carbon system during the ore-thermal recovery of copper slag was created, and the scientific basis and technology of obtaining an iron-containing alloy for white cast iron was developed. As a result, it is possible to obtain an alloy containing iron, which is necessary for obtaining white cast iron.

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