ОБОГАЩЕНИЕ ПОЛЕЗНЫХ ИСКОПАЕМЫХ

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Heavy media separation of coal employing titanomagnetite suspension

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Abstract

Introduction. *Exploring the feasibility of employing iron ore concentrates of various quality and composition as medium solids in heavy media separation of coal is a task of utmost importance for coal beneficiation plants. Titanomagnetite concentrates are promising medium solids being as good as magnetite concentrates as to physical and mechanical properties and processing behavior.*

Research aims *to study the feasibility of using titanomagnetite concentrates of AO Sviatogor as medium solids for AO UK Kuzbassrazrezugol coal beneficiation in heavy suspensions.*

Research methods. *Heavy media separation of –50+25 mm fraction coal was studied using a laboratory facility. Medium solids of various densities were employed and their quality indicators, such as density, size, magnetic fraction content, and stability of the suspension, were determined. Coal was fractionated in zinc chloride.*

Object of research *is titanomagnetite concentrates of the Volkovsky deposit. Float and sink fractions of heavy media separation were examined for total carbon, sulfur, and ash content. Economic benefit from substituting titanomagnetite concentrate for magnetite concentrate was calculated for the Krasnobrodsky coking coal beneficiation plant.*

Research results *have shown that the quality characteristics of titanomagnetite concentrates of the Volkovsky deposit, such as granulometric composition, density, magnetic fraction content, and suspension stability meet the requirements for medium solids used in the process of heavy media separation of coal at AO UK Kuzbassrazrezugol. In the process of heavy media separation, the best result has been obtained under a separation density of 1900 kg/m^3: ash content of the float fraction is 6.57% and total carbon recovery into the float fraction of coal is 95.8%. Under suspension density increase from 1700 to 1900 kg/m^3, it was recorded that the medium solids loss with the beneficiation products has grown by 1.2 times. The results of the heavy media separation of –50+25 mm fraction coal and fractionation in zinc chloride are similar. Economic benefit from substituting Volkovsky titanomagnetite concentrate for Korshunovsky magnetite concentrate at AO UK Kuzbassrazrezugol makes up RUB 66–69 million a year.*

Summary. *Study of heavy media separation with titanomagnetite concentrates of the Volkovsky deposit as medium solids and using coal of AO UK Kuzbassrazrezugol has shown high process performance and economic benefit.*

Keywords: *titanomagnetite concentrate; Volkovsky deposit; coal; medium solids; heavy media separation; suspension stability.*

Introduction. The research aims to examine the feasibility of employing titanomagnetite concentrates of AO Sviatogor and Volkovsky GOK under construction as medium solids for coal beneficiation at AO UK Kuzbassrazrezugol in heavy suspensions.

AO Sviatogor beneficiation plant treats several types of copper and copper-zinc ore including Volkovsky copper-iron-titanium-vanadium ore, from which the titanomagnetite concentrate with the 5–7% content of TiO_2 is obtained after the copper circuit [1, 2]. Besides, Volkovsky GOK has currently passed the design phase and headed over to the construction phase. Volkovsky GOK will process 10 million tons of ore at a separate enterprise manufacturing titanomagnetite concentrate with a high content of titanium [3].

High-titanium titanomagnetite ore with a content of titanium dioxide of more than 3% is scarcely processed globally [4] due to problems associated with the specific character of titanium reduction and the development of infusible masses in the hearth of the blast furnace. Low-titanium iron ore is beneficiated in the Kachkanar GOK with further processing of the agglomerate and pellets at the enterprises of EVRAZ NTMK (Nizhny Tagil Metallurgical Plant). Chinese enterprise of Panzhihua Iron and Steel Company Ltd. is the world's only enterprise to carry out a complete process cycle of low- and high-titanium iron ore.

Main Russian steelworks work at a strictly defined furnace charge which virtually eliminates the use of titanomagnetite concentrate or its palletizing products. There are 3 large titanomagnetite deposits not far from PJSC Magnitogorsk Iron and Steel Works (MMK), namely Medvedevsky, Kopansky, and Suroyamsky deposits. However, despite having a severe shortage of ore, MMK has no plans for developing them and works on the imported ore from Kazakhstan (SSGPO JSC) and Metalloinvest MC LLC since the sinter plant, blast furnace, and convertor require fundamental reconstruction to adjust them to operate on titanomagnetite.

In such conditions, it is important to find fields of titanomagnetite concentrates application other than metallurgical enterprises; fields where physical properties of titanomagnetite concentrates are important, particularly density, size, and magnetic susceptibility, rather than metallurgical properties. This refers to various types of medium solids, including medium solids for heavy media separation (HMS) of coal [5–7].

Materials and methods. The objects of research were two titanomagnetite concentrates: concentrate 1, taken from AO Sviatogor beneficiation plant (BP), and concentrate 2, obtained after concentrate 1 refinement in accordance with the Process Regulations for the Volkovsky GOK BP. The content of chemical components in concentrate 1 sample is: Fe_2O_3 – 59.39%, Cu – 0.031%, S – 0.25%, TiO_2 – 6.90%, V_2O_5 – 1.61%, and P – 0.12%. The content of chemical components in the sample of concentrate 2 is: Fe_2O_3 – 62.70%, Cu – 0.024%, S – 0.11%, TiO_2 – 5.92%, V_2O_5 – 1.46%, and P – 0.014%.

The granulometric composition of the concentrate samples was analyzed using standard screens with openings of 315, 160, 71, 45, and 40 μm and water washing. The –40 μm class was studied on the ADAP apparatus. The density was determined by standard methods [8, 9].

The content of the magnetic fraction in titanomagnetite concentrates was determined on a laboratory tubular magnetic analyzer. The magnetic field strength was 120 kA/m.

A detailed study of the suspension stability parameter is an important step in heavy media separation. The term *suspension stability* means the ability of a finely dispersed powder of a heavy solid to be suspended in a dispersion medium for a long time. The higher the concentration and dispersion of the solid, the higher the stability is [10–12].

In order to analyze the behavior of titanomagnetite suspension consisting of a concentrate and water in different ratios, and the way the concentrate size affects its stability, experiments were carried out to determine the sedimentation time and rate of a suspension with a density of 1700, 1800, and 1900 kg/m^3.

To carry out the experiments, a 2.5-liter cylinder, a stirrer, a ruler, and a stopwatch were used. All experiments were carried out under the same conditions. Before

Table 1. Conditions for suspension stability tests
Таблица 1. Условия проведения опытов по определению устойчивости суспензии

Number of test	Suspension density, kg/m^3	Mass of sample weight, kg		Volume, l				Total content of solid in titanomagnetite suspension, %	Density of titanomagnetite medium solids, kg/m^3
		Titanomagnetite medium solids	Coal slime of –1+0 mm class	medium solids	water	slime	suspension		
1	1700	1.36	0.000	0.31	1.19	0.00	1.5	20.70	4400
	1800	1.55	0.000	0.35	1.15	0.00	1.5	23.30	4400
	1900	1.75	0.000	0.40	1.10	0.00	1.5	26.70	4400
2	1700	1.34	0.000	0.29	1.21	0.00	1.5	19.30	4575
	1800	1.54	0.000	0.34	1.16	0.00	1.5	22.70	4575
	1900	1.73	0.000	0.38	1.12	0.00	1.5	25.30	4575
3	1800	1.55	0.075	0.35	1.14	0.01	1.5	23.70	4400
	1800	1.55	0.150	0.35	1.04	0.11	1.5	30.50	4400
	1800	1.55	0.300	0.35	0.94	0.21	1.5	37.30	4400

Table 2. Conditions for heavy media separation
Таблица 2. Условия проведения тяжелосредной сепарации

Number of test	Amount of slime in suspensions, kg/m^3	Suspension density, kg/m^3	Content of solid in the suspension by volume, %	Mass, kg			Volume, l		
				medium solids	water	slime	suspension	medium solids	water
1	0	1700	21	27.2	23.8	0	30.0	6.2	23.8
2	0	1800	24	31.0	23.0	0	30.0	7.0	23.0
3	0	1900	26	34.9	22.1	0	30.0	7.9	22.1

measurements, the suspension was thoroughly mixed with a stirrer in a flask for 2 min, then the height of the clarified layer was measured for 5 min after a certain period of time (30 s). The experimental conditions for stability determination of a suspension based on titanomagnetite concentrates are given in Table 1.

To carry out the actual experiments on HMS, a sample of coal and rock with a fraction of –50+25 mm was assembled in a ratio close to the original machine grade of the Krasnobrodsky– Koksovaya (Coking) coal beneficiation plant (CBP).

Fractional analysis of a coal sample in zinc chloride with a density of 1400, 1500, and 1800 kg/m^3 collected at AO UK Kuzbassrazrezugol and the obtained fractions yield and quality assessment were carried out in accordance with the requirements and procedures of GOST 4790-93 “Solid fuel. Determination and presentation of float and sink characteristics. General directions for apparatus and procedures”. Fractionation was carried out in zinc chloride solutions of specified densities starting with the lowest density solution.

Table 3. Granulometric composition of titanomagnetite concentrates 1 and 2 in accordance with the requirements of normative documents (ND), %
Таблица 3. Гранулометрический состав титаномагнетитовых концентратов 1 и 2 в соответствии с требованиями НД, %

Size, μm	Grade F (fine)		Grade T (thin)	
	content of fractions in accordance with ND, %	actual value of fractions content, %	content of fractions in accordance with ND, %	actual value of fractions content, %
Less than 20	10–25	7	25–35	3
Less than 40	50–60	52	60–75	74
More than 150	2–10	3	0–5	0

Coal samples HMS were studied on a heavy-medium laboratory facility. The –50+25 mm gain size machine grade was prepared for separation by washing the material with water on a screen with openings of 1.0 mm.

To calculate the masses and densities of the titanomagnetite suspension in the experiments, the density of water was 1000 kg/m^3, and the medium solids density according to the analysis results was 4400 kg/m^3. The main formulae for suspension parameters calculation were taken from [13, 14]. In these experiments, all calculations were made for suspension active volume of 30 l (0.03 m^3). The experimental conditions are given in Table 2.

Coal separation in titanomagnetite suspension was carried out starting from the suspension lowest density of 1700 kg/m^3. For the purposes of monitoring, prior to each experiment, the actual density of the active suspension was determined by collecting and weighing the particular amount of pulp.

The mass, ash content, and content of total carbon, and the content of total sulfur were determined in separation products. The losses of medium solids with beneficiation products were further determined.

Results and discussion. *Titanomagnetite concentrates analysis for compliance with the requirements to magnetite medium solids.*

The results of granulometric composition analysis of concentrates 1 and 2 and its comparison to the requirements of the normative documents (ND) are presented in Table 3 [8, 9].

According to analysis results, concentrate 1 can be attributed to size grade F (fine), while titanomagnetite concentrate 2 can be attributed to size grade T (thin).

It should be noted that titanomagnetite concentrates 1 and 2 have a smaller amount of slime and coarse fractions as compared to the regulated ones and, as a consequence, a more stable granulometric composition, which is good for suspension stability.

The practice of coal enterprises using HMS has shown [8] that coal beneficiation plants work on iron concentrates of intermediate size. The plants of AO UK Kuzbassrazrezugol use the Korshunovsky GOK iron concentrate supplied according to specifications as a magnetite suspension. Only the class of more than 150 μm (no more than 20%) is subject to regulation. The remaining indicators are provided for reference. Therefore, concentrates 1 and 2 meet the size requirements for medium solids.

Table 4. The results of suspension stability determination under different densities
Таблица 4. Результаты определения устойчивости суспензии при различной плотности

Time, s	Height of clarification, m, under suspension density, kg/m^3					
	actual			design		
	1700	1800	1900	1700	1800	1900
Test 1, concentrate 1, ρ_m = 4400 kg/m^3						
30	0.022	0.034	0.011	0.022	0.034	0.011
60	0.045	0.044	0.018	0.023	0.010	0.007
90	0.060	0.055	0.021	0.015	0.011	0.003
120	0.080	0.066	0.035	0.020	0.011	0.014
150	0.095	0.078	0.044	0.015	0.012	0.009
180	0.115	0.089	0.055	0.020	0.011	0.011
210	0.130	0.100	0.063	0.015	0.011	0.008
240	0.141	0.109	0.070	0.011	0.009	0.007
270	0.151	0.117	0.079	0.010	0.008	0.009
300	0.160	0.126	0.087	0.009	0.009	0.008
Mean value				0.016	0.013	0.009
Clarification rate, m/s				0.000053	0.000042	0.000029
Test 2, concentrate 2, ρ_m = 4575 kg/m^3						
30	0.021	0.011	0.005	0.021	0.011	0.005
60	0.055	0.020	0.007	0.034	0.009	0.002
90	0.086	0.029	0.012	0.031	0.009	0.005
120	0.100	0.037	0.015	0.014	0.008	0.003
150	0.110	0.044	0.020	0.010	0.007	0.005
180	0.114	0.049	0.023	0.004	0.005	0.003
210	0.118	0.054	0.026	0.004	0.005	0.003
240	0.122	0.060	0.030	0.004	0.006	0.004
270	0.125	0.064	0.032	0.003	0.004	0.002
300	0.131	0.068	0.034	0.006	0.004	0.002
Mean value				0.013	0.007	0.003
Clarification rate, m/s				0.000044	0.000023	0.000011

The average material density of titanomagnetite concentrates 1 and 2 according to four measurements was 4400 kg/m^3 for concentrate 1 and 4575 kg/m^3 for concentrate 2. Thus, according to the analysis, the density of titanomagnetite concentrates 1 and 2 corresponds to the recommended density range for magnetite medium solids 4300–4600 kg/m^3 [5, 6].

According to the results of magnetic analysis, the content of magnetic fraction in titanomagnetite concentrate 1 made up 97.02%, which meets the requirements for magnetite medium solids (not less than 90%). Titanomagnetite concentrate 2 has an even higher content of magnetic fraction due to a higher content of iron.

The results of studying the suspension clarification height (stability) at different densities of titanomagnetite are given in Table 4, where ρ_m is the true density of medium solids.

Table 5. Results of heavy media separation of –50+25 mm coal fraction
Таблица 5. Результаты тяжелосредной сепарации угля фракции –50+25 мм

Number of test	Product	Yield		Content, %			Recovery $C_{total.}$, %
		product, %	medium solids, g	$C_{total.}$	$S_{total.}$	Ash content, %	
1	Float fraction	73.96	19.76	67.50	0.49	8.17	91.0
	Sink fraction	26.04	8.29	19.00	0.74	66.10	9.0
	Total	100.00	28.05	54.87	0.55	23.25	100.0
2	Float fraction	76.91	23.85	65.90	0.46	7.48	94.7
	Sink fraction	23.09	6.85	12.30	0.49	72.00	5.3
	Total	100.00	30.70	53.52	0.47	22.38	100.0
3	Float fraction	77.59	26.58	67.10	0.45	6.57	95.8
	Sink fraction	22.41	7.08	10.20	0.37	74.20	4.2
	Total	100.00	33.66	54.35	0.43	21.73	100.0

It follows from Table 4 that the titanomagnetite suspension clears up over time, and the more time passes, the less intensive the process is.

According to the results of suspension stability analysis, it was found that as the density of the titanomagnetite suspension increases from 1700 to 1900 kg/m^3, the clarification height of the medium solids decreases from 0.016 m to 0.009 m for concentrate 1, and from 0.013 m to 0.003 m for concentrate 2.

Thus, suspension density growth results in its greater stability.

The lowest particle clarification rate was obtained at a suspension density of 1900 kg/m^3 – 0.000029 m/s (concentrate 1) and 0.000011 m/s (concentrate 2). The total content of solid in the suspension at this density was 26.7 and 25.3%, respectively, which defines the suspension as sufficiently stable with an admissible viscosity level of no more than $7 \cdot 10^{-3}$ Pa · s [12, 15].

The results of analyzing the rate of titanomagnetite suspension clarification show that the higher the suspension density, the lower the rate of titanomagnetite subsidence, and therefore the higher the suspension stability.

Besides, the finer concentrate 2 has lower suspension clarification rates, which means that with a decrease in the medium solids size, the stability index of the suspension increases.

It follows from the research results that a higher stability of the titanomagnetite suspension was obtained at a density of 1900 kg/m^3 on both concentrates.

Coal fractionation. Heavy media separation. As part of the research on coal sample fractionation in zinc chloride, it was found that pieces of coal in the sample have a rather wide density range – from less than 1400 to more than 1800 kg/m^3. Most of the coal is concentrated in a fraction with a density of less than 1400 kg/m^3.

According to the established classification for hard coal applied for energy purposes, the rock fraction yield is estimated based on a density of more than 1800 kg/m^3, while the concentrate yield is estimated based on a density of less than 1800 kg/m^3.

a *b*

Fig. 1. Illustration of the experiment – *a*, the end product – *b*
Рис. 1. Иллюстрация эксперимента – *a*, конечный продукт – *b*

When studied for coal fractionation in zinc chloride at densities of 1400, 1500, and 1800 kg/m^3, the theoretical yield of concentrate made up 66.07% with an ash content of 5.89%, the theoretical yield of a middling product made up 7.44% with an ash content of 24.09–36.68%, and the yield of waste made up 26.49% with ash content 73.46%.

The experimental results of –50+25 mm coal fraction HMS are presented in Table 5.

As a result of tests on HMS of –50+25 mm class coal sample in titanomagnetite suspension of different densities (1700–1900 kg/m^3), the following has been defined:

– the best result has been obtained with a separation density of 1900 kg/m^3: the ash content of float fraction is 6.57%, the total carbon recovery in coal float fraction is 95.8%;

– as the density of the suspension grows from 1700 to 1900 kg/m^3, it has been recorded that the loss of medium solids with beneficiation products grows by 1.2 times.

Figure 1 presents an illustration of the experiment and the float product.

According to the features of the concentrates obtained at JSC UK Kuzbassrazrezugol, the ash content is in the range of 5.8–9.2%. Thus, the obtained result (6.57%) falls into this range.

Comparison results of the coal quality analysis after laboratory HMS and the data of fractionation in zinc chloride according to the standard method are given in Table 6. Data comparison showed that they are comparable both in products material composition and coal washability.

The economic benefit for the Krasnobrodsky coal beneficiation plant of JSC UK Kuzbassrazrezugol was calculated based on the research results.

The economic benefit of substituting titanomagnetite concentrate of AO Sviatogor for the Korshunovsky iron concentrate for 1 ton of concentrate made up RUB 7,693.4, and for the entire quantity of annual supplies the economic benefit made up RUB 66.1 million.

When using titanomagnetite concentrate from the new Volkovsky beneficiation plant, the economic benefit for 1 ton of concentrate made up RUB 8,077.9, and for the entire quantity of annual supplies the economic benefit made up RUB 69.4 million.

Table 6. Comparison results of fractionation and heavy media separation
Таблица 6. Сравнительные результаты фракционирования и тяжелосредной сепарации

Indicator	Values, %	
	HMS	fractionation
	Material composition of the source	
Ash content	22.50	23.70
Content of volatile substances ignoring the content of moisture	47.10	47.20
	Process performance of fractionation	
Fraction with a density of more than 1800 kg/m^3:		
yield	22.41–23.09	26.49
ash content	72.00–74.20	73.46
Fraction with a density of less than 1800 kg/m^3:		
yield	73.96–76.91	73.51
ash content	7.48–8.17	8.73

Summary. Titanomagnetite concentrates with the content of titanium dioxide of more than 3% are currently scarcely used in metallurgical production.

The study of Volkovsky titanomagnetite concentrates qualitative characteristics, including the granulometric composition, density, magnetic fraction content and suspension stability, has shown that they may be employed as medium solids in the process of heavy media separation of coal at JSC UK Kuzbassrazrezugol.

According to laboratory studies, the best result of heavy media concentration of coal with –50+25 mm fraction in titanomagnetite suspension was obtained at a separation density of 1900 kg/m^3: ash content of the float fraction is 6.57% and recovery of total carbon in the floating fraction is 95.8%.

Comparison of the experimental results on heavy media separation to the data of traditional coal fractionation in zinc chloride has shown that they are comparable both in products material composition and in coal washability.

The economic benefit of substituting Volkovsky titanomagnetite concentrate for Korshunovsky iron concentrate at JSC Kuzbassrazrezugol made up RUB 66–69 million a year.

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Исследование тяжелосредной сепарации угля с использованием титаномагнетитовой суспензии

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Реферат
Введение. *Исследование возможности использования железорудных концентратов разного качества и состава как утяжелителей в процессе тяжелосредной сепарации угля является актуальной задачей для углеобогатительных фабрик. Титаномагнетитовые концентраты являются перспективными утяжелителями и не уступают магнетитовым концентратам по физико-механическим и технологическим свойствам.*
Цель работы *– изучение возможности использования титаномагнетитовых концентратов АО «Святогор» в качестве утяжелителя при обогащении угля АО «УК Кузбассразрезуголь» в тяжелых суспензиях.*
Методология. *Проводились исследования тяжелосредной сепарации угля фракции –50+25 мм на лабораторной установке с использованием утяжелителей различной плотности и определением их показателей качества, таких как плотность, крупность, содержание магнитной фракции и устойчивость суспензии. Проводилось фракционирование угля в хлористом цинке.*
Объектом исследований *являлись титаномагнетитовые концентраты Волковского месторождения. Всплывшая и потонувшая фракции тяжелосредной сепарации исследовались на содержание общего углерода, серы и зольности. Рассчитывался экономический эффект от замены магнетитового концентрата на титаномагнетитовый для Краснобродской коксовой углеобогатительной фабрики.*

Результаты исследований *показали, что качественные характеристики титаномагнетитовых концентратов Волковского месторождения, такие как гранулометрический состав, плотность, содержание магнитной фракции и устойчивость суспензии, соответствуют требованиям к утяжелителям, используемым в процессе тяжелосредной сепарации угля на АО «УК Кузбассразрезуголь». Лучший результат в процессе тяжелосредной сепарации получен при плотности разделения 1900 кг/м^3: зольность всплывшей фракции составляет 6,57 %, извлечение общего углерода во всплывшую фракцию угля – 95,8 %. При увеличении плотности суспензии с 1700 до 1900 кг/м^3 отмечено увеличение потерь утяжелителя с продуктами обогащения в 1,2 раза. Результаты тяжелосредной сепарации угля фракции –50+25 мм и фракционирования в хлористом цинке близки. Экономический эффект от замещения Коршуновского магнетитового концентрата на АО «УК Кузбассразрезуголь» на титаномагнетитовый концентрат Волковского месторождения составляет 66–69 млн р./год.*

Выводы. *Исследования процесса тяжелосредной сепарации с применением титаномагнетитовых концентратов Волковского месторождения в качестве утяжелителя на угле АО «УК Кузбассразрезуголь» продемонстрировали высокие технологические показатели и экономический эффект.*

Ключевые слова: *титаномагнетитовый концентрат; Волковское месторождение; уголь; утяжелитель; тяжелосредная сепарация; устойчивость суспензии.*

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