UDC 546.74 : 66.081
https://doi.org/10.17073/0021-3438-2024-3-25-33

Research article
Научная статья

Hydrometallurgical recovery of nickel from oxidized ores

V.I. Dudarev, G.N. Dudareva, A.A. Yakovleva

Irkutsk National Research Technical University
83 Lermontova Str., Irkutsk 664074, Russia

✉ Vladimir I. Dudarev (vdudarev@mail.ru)

Abstract: A significant portion of the world's reserves of Ni-containing raw materials (40–66 %) is concentrated in oxidized nickel ores. One of the alternatives to the high-cost pyrometallurgical and ammonia-carbonate methods for processing such ores could be the chlorammonium recovery of nickel from relatively low-grade ores. The halide-ammonia decomposition and recovery technology of nickel from oxidized nickel ores, supplemented by a sorption process, is less stage-intensive and simpler in practical implementation. Nickel adsorption recovery is feasible using carbon sorbents that exhibit high chemical stability, withstand high-temperature exposure, and strong acidic treatment. Sorbents were obtained through steam-gas activation of extracted carbonizates from fossil coals. The sorption capacity for Ni(II) ions was studied, and the patterns and characteristic parameters of the process on carbon sorbents were identified using adsorption isotherms while varying experimental conditions. The experimental results were processed using the Freundlich and Langmuir equations. The sorbents have several distinctive features determined by their predominant microporous structure and multifunctional surface with active complex-forming atomic groups, characteristic of ampholytes with cation- and anion-exchange properties. The adsorption process is described by a pseudo-first-order equation with rate constants ranging from 0.204 to 0.287 s^{-1}. For the adsorption recovery of Ni(II), a scheme with two adsorbers and a pseudo-fluidized sorbent bed is proposed. Nickel desorption and sorbent regeneration were carried out with a 2.3 % sulfuric acid solution, desorbing 95 to 98 % of nickel. Standard chemical machinery and equipment are recommended for these processes.

Keywords: oxidized ores, carbon sorbents, nickel recovery.

For citation: Dudarev V.I., Dudareva G.N., Yakovleva A.A. Hydrometallurgical recovery of nickel from oxidized ores. *Izvestiya. Non-Ferrous Metallurgy*. 2024;30(3):25–33. https://doi.org/10.17073/0021-3438-2024-3-25-33

Гидрометаллургическое извлечение никеля из окисленных руд

В.И. Дударев, Г.Н. Дударева, А.А. Яковлева

Иркутский национальный исследовательский технический университет
664074, Россия, г. Иркутск, ул. Лермонтова, 83

✉ Владимир Иванович Дударев (vdudarev@mail.ru)

Аннотация: Большая часть мировых запасов Ni-содержащего сырья (40–66 %) сосредоточена в окисленных никелевых рудах. Одной из альтернативных высокозатратным пирометаллургическому и аммиачно-карбонатному методам переработки таких руд может быть хлораммонийное извлечение никеля из относительно бедных по содержанию металла руд. Технология галогенидно-аммиачного разложения и извлечения никеля из окисленных никелевых руд, дополненная сорбционным процессом, является менее длительной по стадийности и проще в практическом исполнении. Адсорбционное извлечение никеля возможно углеродными сорбентами, обладающими высокой химической устойчивостью, выдерживающими высокотемпературное воздействие и сильнокислотную обработку. Сорбенты получены путем парогазовой активации выделенных карбонизатов ископаемых

паемых углей. Изучена сорбционная способность ионов Ni(II), выявлены закономерности и характеристические параметры процесса на углеродных сорбентах с помощью изотерм адсорбции при варьировании условий проведения экспериментов. Обработку экспериментальных результатов выполняли с использованием уравнений Фрейндлиха и Ленгмюра. Сорбенты имеют ряд особенностей, определяемых преобладающей микропористой структурой и полифункциональной поверхностью с активными комплексообразующими группировками атомов, характерными для амфолитов с катионо- и анионообменными свойствами. Процесс адсорбции описан уравнением псевдопервого порядка с константами скорости от 0,204 до 0,287 c^{-1}. Для адсорбционного извлечения Ni(II) предложена схема с двумя адсорберами и псевдоожиженным слоем сорбента. Десорбция никеля и регенерация сорбента проведены 2,3 %-ным раствором серной кислоты. При этом десорбируется от 95 до 98 % никеля. В процессах рекомендуются стандартные химические машины и аппараты.

Ключевые слова: окисленные руды, углеродные сорбенты, извлечение никеля.

Для цитирования: Дударев В.И., Дударева Г.Н., Яковлева А.А. Гидрометаллургическое извлечение никеля из окисленных руд. *Известия вузов. Цветная металлургия*. 2024;30(3):25–33. https://doi.org/10.17073/0021-3438-2024-3-25-33

Introduction

In the global reserves of Ni-containing raw materials, a significant portion (from 40 to 66 %) is composed of oxidized nickel ores (ONO) [1—3], in which the average Ni content is only 0.7—1.2 %. Therefore, their targeted processing by pyrometallurgical methods is high-cost and, as a rule, unprofitable [2—4]. The combined scheme for processing ONO developed by scientists at the Ural Federal University named after the first President of Russia B.N. Yeltsin (Yekaterinburg) [5] (thermochemical treatment — aqueous leaching — hydroxide precipitation) allows obtaining a nickel concentrate, which enhances the economic feasibility of applying pyrometallurgical technology. However, the scheme involves thermochemical treatment of the entire ore mass, including barren rock, as well as requiring preliminary treatment of ONO with significant volumes of hydrochloric acid and roasting to obtain insoluble forms of interfering components. All this significantly complicates the process of nickel recovery.

Researchers at Tomsk Polytechnic University [6; 7] propose using a single reagent, ammonium chloride, for the initial processing of ONO. The main ore mass, including SiO_2 oxides (51 %) and Al_2O_3 (5 %), does not interact with the reagent, while oxides of other associated metals start interacting at a temperature of 473 K. Nickel oxide transitions to a water-soluble nickel chloride through an intermediate product $NiCl_2 \cdot nNH4Cl$ at $T = 600$ K. Subsequent aqueous leaching of the thermally treated ore and ammonia precipitation of hydroxides allow sequential separation of ONO into individual target components [6]. Incorporating a sorption process into such innovative technology can significantly enhance the efficiency of nickel recovery from ONO [8; 9].

The adsorption recovery of nickel is possible with sorbents from various raw materials, including carbon sorbents, which have a developed porous structure with a specific surface area of more than 500 m^2/g [10—21]. Carbon sorbents of the AD type, synthesized at INRTU, possess high chemical stability, withstand high-temperature exposure, and resist strong acid treatment [22; 23]. They have several features defined by their microporous structure and multifunctional surface with active complex-forming atomic groups, characteristic of ampholytes with cation- and anion-exchange properties [24].

Sorbents obtained through steam-gas activation of extracted carbonizates from fossil coals are dark granules of irregular shape with an average particle size of 1 to 2 mm, a specific surface area of 550 m^2/g, mechanical abrasion resistance of 82 %, a total pore volume (by water) of 0.61 cm^3/g, iodine adsorption activity of 84 %, and a bulk density of 560 g/dm^3 [23].

The aim of this work was to study the adsorption characteristics of the AD carbon sorbent and to develop recommendations for the hydrometallurgical recovery of nickel from oxidized ores.

Research methodology

The analysis of the sorption capacity for nickel ions, the identification of regularities, and characteristic parameters of the process were carried out using adsorption isotherms while varying the experimental conditions in both static and dynamic modes. The structure, porosity, and surface compound properties of the sorbents were studied using various physicochemical methods with modern instrumentation [24—26].

The AD sorbent possesses amphoteric ion-exchange properties. The ion-exchange capacity was determined by reverse titration methods using 0.1 N solutions of HCl and NaOH. The cation-exchange capacity for H^+ was 0.92 meq/g, and the anion-exchange capacity for OH^- was 7.52 meq/g. These data indicate that the sorbent surface contains functional groups with exchangeable H^+ and OH^- ions that can be replaced by metal ions. The optimization of nickel sorption recovery was carried out by varying the acidity and temperature of the solutions, as well as considering the nature of the adsorption on the porous material surface.

The effect of medium acidity on sorption capacity was evaluated under static conditions. A 0.5 g sample of the adsorbent was placed in 100 cm^3 of a solution prepared from reagent-grade nickel chloride. The reaction flask volume was 250 cm^3, and the initial metal concentration in the solution was 0.51 mmol/dm^3. The pH value in the range of 3 to 11 was adjusted using ammonia-acetate buffer solutions. A magnetic stirrer was used for mixing until adsorption equilibrium was established.

Quantitative analysis of nickel was performed by spectrophotometric methods using analytical reagents such as dimethylglyoxime or N-acyl-acetohydrazone [26]. Periodically, additional control of nickel ion concentration in solutions and the metal content in the sorbent after thermo-acid decomposition of the dried sorbent was carried out by atomic absorption analysis according to standard methodology [27]. The adsorption amount (A, mmol/g) was calculated using the formula

$$A = (C_0 - C_p)V/m, \tag{1}$$

where C_0 and C_p are the initial and equilibrium concentrations of the adsorbate, respectively, mmol/dm^3; m is the mass of the adsorbent, g; V is the volume of the working solution, dm^3.

Studies at elevated temperatures were conducted in thermostated cells.

Results and discussion

The nature of the sorption interaction, observed at temperatures of 298, 318, and 338 K, is shown by the adsorption isotherms of Ni(II) ions on the carbon sorbent (Fig. 1).

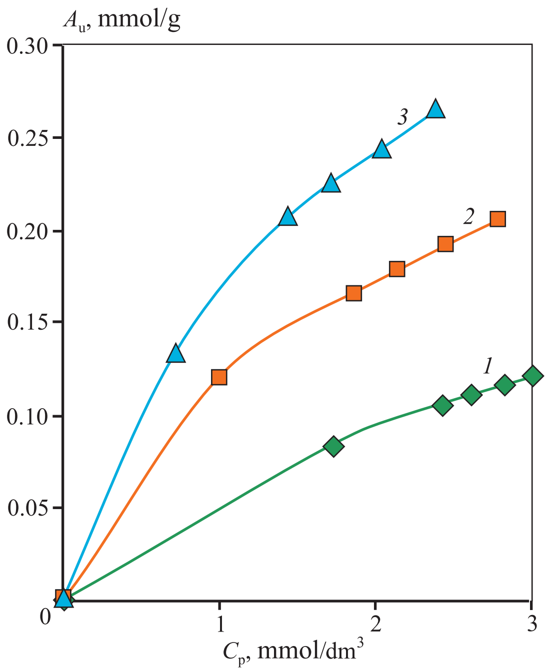

Fig. 1. Adsorption isotherms of Ni (II) ions at temperatures 298 K (***1***), 318 K (***2***), and 338 K (***3***)

A_u – concentration of metal on the sorbent

Рис. 1. Изотермы адсорбции ионов Ni(II) при температурах 298 K (***1***), 318 K (***2***) и 338 K (***3***)

A_u – концентрация металла на сорбенте

The processing of experimental results in the low nickel concentration range in solutions was performed using the classical Freundlich equation:

$$A = K_F C_p^{1/n}. \tag{2}$$

After performing arithmetic transformations and plotting the linear dependence of the logarithmic form of the equation:

$$\lg A = \lg K_F + 1/n \lg C_p \tag{3}$$

both constant parameters K_F and n were determined graphically. The constant K_F represents the millimolar adsorption coefficient, as it corresponds to the adsorption value at an adsorbate concentration $C = 1$ mmol/dm^3. The exponent $1/n$ is a proper fraction and generally characterizes the degree of the adsorption isotherm's approach to the abscissa axis. From the data presented in Table 1, it follows that with increasing temperature, both constants of the Freundlich equation (2)

Table 1. **Constants of the Freundlich equation (R^2 = 0.92)**

Таблица 1. Константы уравнения Фрейндлиха (R^2 = 0,92)

Constants	Temperature, K		
	298	318	338
K_F	0.19	0.25	0.29
n	1.73	1.84	1.94

increase. The value of the coefficient K_F suggests that the adsorption of Ni(II) ions in the initial period occurs with high efficiency.

To describe the process upon reaching the adsorption limit, the Langmuir equation was used. In its linear form, it is represented as a straight-line equation:

$$1/A = 1/A_\infty + 1/A_\infty K_p C, \tag{4}$$

where C is the concentration of the metal in the solution, mmol/dm^3; A_∞ are the ultimate adsorption values, mmol/g; K_p is the adsorption equilibrium constant.

By plotting the dependence in the coordinates $1/A = f(1/C)$, the constants A_∞ and K_p in the Langmuir equation were determined graphically. The results are presented in Table 2.

It is evident that temperature affects both the ultimate adsorption value and the adsorption equilibrium constants, which also increase with temperature.

Analysis of the results shows that the process of nickel adsorption on the carbon sorbent is not purely physical adsorption. The standard thermodynamic parameter, Gibbs free energy (ΔG), was calculated using the classical chemical affinity equation:

$$\Delta G = -RT \ln K_p, \tag{5}$$

where R = 8.314 J/mol·K is the universal gas constant; T is the process temperature in K.

From the data presented in Table 2, it is evident that with increasing temperature, the likelihood of the spontaneous adsorption process increases.

For the graphical determination of the adsorption enthalpy of Ni(II), the isobar equation in its differential form was used:

$$\ln K_p = \frac{\Delta H}{RT}. \tag{6}$$

As a result, its value was –8.96 kJ/mol (see Table 2).

The evaluation of kinetic regularities was conducted using the classical method of selecting the axes of kinetic equations. The linear dependencies $\ln C = f(t)$ at all temperatures (Fig. 2) confirm that the adsorption process is described by a pseudo-first-order equation. The values of the rate constants (k_c) obtained in this way are presented in Table 2.

Contrary to the Van't Hoff rule for homogeneous chemical reactions, the adsorption rate constant grows significantly slower, indicating the complexity of the process mechanism. This is also confirmed by the activation energy (E_a), graphically determined by linearizing the Arrhenius equation:

$$\ln k = \ln k_0 \frac{E_a}{RT}. \tag{7}$$

The experimentally determined activation energy for the adsorption process was 7.1 kJ/mol, indicating the process occurs in the diffusion region [28].

To address the question of the limiting stage of adsorption, experiments with process interruption in dynamic mode were conducted for a specified time. The results showed that in all cases, a 24-hour inter-

Table 2. **Thermodynamic sorption constants (R^2 = 0.96)**

Таблица 2. Термодинамические константы адсорбции (R^2 = 0,96)

Parameter	Temperature, K		
	298	318	338
A_∞, 10^{-4} mmol/g	1.01	1.53	1.66
K_p	394	416	524
k_c, s^{-1}	0.204	0.229	0.287
ΔG, kJ/mol	–20.5	–22.1	–24.7
ΔH, kJ/mol		–8.96	
E_a, kJ/mol		7.1	

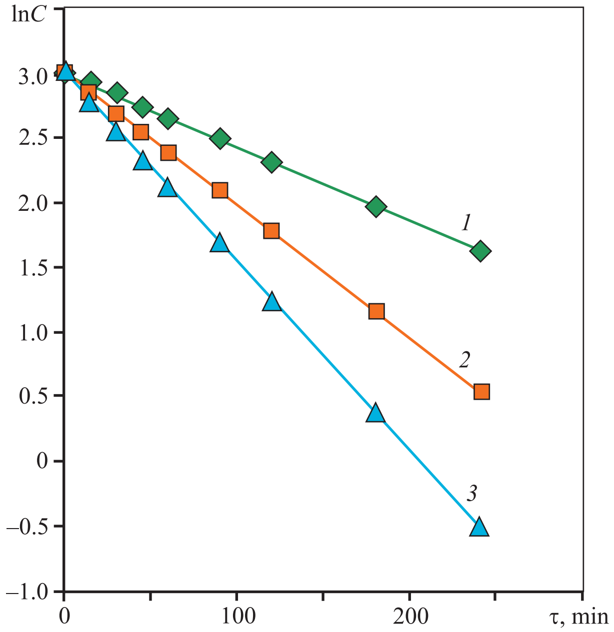

Fig. 2. Kinetic dependences of Ni(II) ion sorption at temperatures 298 K (*1*), 318 K (*2*), and 338 K (*3*)

Рис. 2. Кинетические зависимости сорбции ионов Ni(II) от температуры 298 K (*1*), 318 K (*2*) и 338 K (*3*) ruption of the adsorption flow resulted in a decreased concentration of the adsorbed metal in the solution exiting the column. The discontinuity in the adsorption exit curves suggests that the limiting stage of the adsorption kinetics of Ni(II) ions on the carbon adsorbent under the studied conditions is diffusion within the adsorbent granules, i.e., adsorption occurs under "gel" kinetics, and its rate is hindered by intradiffusion processes. The possible sorption mechanism can be considered as the diffusion process of complex Ni(II) ions, specifically the hydroxo-pentaammin cation $[Ni(NH_3)_5(OH)]^+$, into the granules and their interaction with functionally active groups on the sorbent surface through ion exchange.

Studies using IR spectroscopy methods showed that the observed results of metal ion sorption involve the participation of double bonds of compound fragments located on the carbon surface. Changes were observed in the overtones of $=CH_2$, $=C—NH_2$, and $=C—OH$ bonds, as well as in the conjugated fragments of $=C=C=C=$ and $R—C=O$, $R—OH$ bonds. This indicates the participation of π-electrons of these molecular fragments or their exchange parts in the reactions. They likely act as electron pair donors, with the free *d*-orbitals of the adsorbed metal serving as acceptors in the corresponding complexes. This conclusion confirms the nature of metal ion interaction with the adsorbent surface. The appearance of bands in its spectrum after metal ion sorption at $\nu = 574$, 604, and 836 cm^{-1}, corresponding to the characteristic deformation vibration bands of $Me—O—C$ and $Me—O—Me$ bonds, indicates the presence of such bonds in the investigated compounds.

The analysis of results also showed that during adsorption, with increasing temperature, the sorbent's capacity for nickel increases. The adsorption of Ni(II) ions in this case does not correspond to the classical behavior of metal ions: for many of them, adsorption results in an exothermic effect [29]. It is likely that the high stability of associated nickel compounds: amine complexes ($K_u = 5{,}3\cdot10^8$), aqua-amine complexes ($K_u = 4{,}2\cdot10^6$), and hydroxo-amine complexes ($K_u = 5{,}8\cdot10^6$) [26], predetermines the need for additional energy to break them down before sorption. This energy may be greater than the energy of the exothermic ion exchange reaction when Ni(II) is fixed on the sorbent surface, making the overall sorption process appear endothermic.

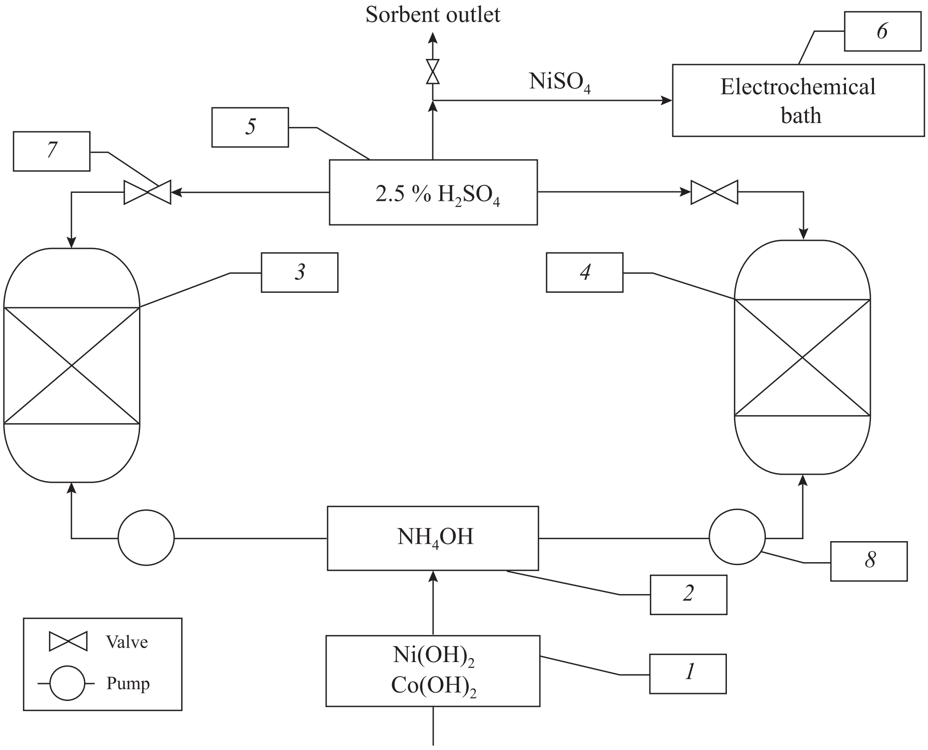

Fig. 3. Schematic diagram of the apparatus chain for nickel sorption extraction
1, ***2***, ***5***, ***6*** –solution tanks; ***3***, ***4*** – adsorbers; ***7*** – valves; ***8*** – pumps

Рис. 3. Схема цепи аппаратов для сорбционного извлечения никеля
1, ***2***, ***5***, ***6*** – емкости для растворов; ***3***, ***4*** – адсорберы; ***7*** – вентили; ***8*** – насосы

In the chlorammonium technology for nickel recovery from oxidized ores, the active reagent used for the technological transformation of metal oxides is regenerated and returned to the head of the process for the decomposition of a new batch of ONO [6]. The selectivity of ammonium chloride allows for the initial stage to free most of the ore. During ore opening, 75 % of nickel is extracted as hydroxide [7]. It seems reasonable to introduce a stage of adsorption recovery of nickel in the process of separating the technological solution, where precipitation and separation of nickel hydroxide will occur at pH = 8.0÷8.5 [8]. For the adsorption recovery of Ni(II), a scheme with two adsorbers with a pseudo-fluidized sorbent bed is proposed (Fig. 3).

During the adsorption studies, insights into the process mechanism were obtained, enabling the development of practical recommendations for implementing the proposed scheme. Before initiating the process, it is necessary to adjust the acidity of the technological solution to optimal values, which is achieved by adding an ammonium hydroxide solution. The solution is pumped from the bottom into the adsorber for the adsorption process. Compared to other designs, adsorbers with a pseudo-fluidized sorbent bed offer advantages such as an increased phase contact area with the same loading volume and a longer phase contact time.

For the adsorption recovery of metal, a cylindrical column design with a conical bottom and distribution grids inside the apparatus was chosen. To organize a continuous recovery process, two adsorbers are used: after the sorbent in the first unit becomes saturated, it switches to reloading while the second unit switches to adsorption. After reloading, the sorbent is directed to a desorber equipped with a stirrer, where a diluted (1 : 20, or 2.3 %) sulfuric acid solution is supplied. It was found that using H_2SO_4 at this concentration as the eluent desorbs 95 to 98 % of the nickel. The saturated Ni(II) solution after desorption is proposed for use in the electrolytic recovery of the metal.

When operating the sorption columns, it should be noted that the degree of nickel recovery from solutions decreases by 3—5 % after each cycle. The adsorbers should be switched before complete saturation of the load, as at times close to full saturation of the adsorbent, the concentration of metals in the solution approaches equilibrium, and the adsorption rate realistically decreases. The estimated total operating time of one adsorber before reloading the carbon is 648 hours. It is advisable to use only standard chemical machinery and apparatus in the processes.

Conclusion

The chlorammonium hydrometallurgical technology for nickel recovery from oxidized ores is based on the solid-phase chlorination of oxidized nickel ores with ammonium chloride at T = 473 K, followed by aqueous leaching of soluble nickel chlorides and other valuable components. It is advisable to include a nickel adsorption recovery process in the above-mentioned technological scheme at the stage of obtaining ammonia solutions (Ni^{2+}, Co^{2+}, Mn^{2+}, Mg^{2+}, Ca^{2+}). It is most likely that after precipitation, the metals are present in the technological solution as complex ammines.

The study showed that adsorption interaction in the "metal-containing solution — carbon sorbent" system proceeds quite intensively: the rate constants range from 0.204 до 0.287 s^{-1}. The activation energy value (E_a = = 7.1 kJ/mol) indicates that the adsorption process occurs in the diffusion region. The change in Gibbs free energy ($\Delta H = -8.96$ kJ/mol) suggests that the likelihood of the spontaneous adsorption process increases with temperature.

For the adsorption recovery of Ni(II), a scheme with two adsorbers with a pseudo-fluidized sorbent bed and bottom supply of a weakly alkaline technological solution is proposed. Nickel desorption is carried out with a 2.3 % sulfuric acid solution, desorbing 95 to 98 % of the nickel.

References

1. Naftal M.N., Dyachenko V.T., Serova N.V., Bryukvin V.A., Lysykh M.P. Oxidized nickel ores are a promising source of mineral raw materials for increasing the production of nickel and cobalt in LLC MMK Norilsk Nickel. *Tsvetnye metally.* 2012;6:25—28. (In Russ.).
   Нафталь М.Н., Дьяченко В.Т., Серова Н.В., Брюквин В.А., Лысых М.П. Окисленные никелевые руды — перспективный источник минерального сырья для повышения объемов производства никеля и кобальта в ОАО «ГМК «Норильский никель». *Цветные металлы*. 2012;6:25—28.
2. Reznik I.D. , Ermakov G. P., Shneerson Ya.M. Nickel. Vol. 2. Moscow: Nauka i Tekhnologiya, 2001. 468 p. (In Russ.).
   Резник И.Д., Ермаков Г.П., Шнеерсон Я.М. Никель. Т. 2. М.: Наука и технология, 2001. 468 с.
3. Kalashnikova M.I. Development of scientific foundations for the creation of new and improvement of existing hydrometallurgical technologies for processing of ore raw materials and intermediate products of copper-nickel production: Abstract of the Dissertation of Dr. Sci. (Eng.). St. Petersburg: SPbSPU, 2007. (In Russ.).

Калашникова М.И. Разработка научных основ создания новых и совершенствования действующих гидрометаллургических технологий переработки рудного сырья и промежуточных продуктов медно-никелевого производства: Автореф. дисс. ... докт. техн. наук. Санкт-Петербург: СПбГПУ, 2007.

4. Chunarev A.A., Kolmachikhina O.B., Naboychenko S.S. Overview of methods for processing oxidized nickel ores and prospects for the development of nickel production in the Urals. In: *Ural industrialny. Bakunin's Readings: Industrial Modernization of the Urals in the XVIII–XXI Centuries:* Mater. XII Al-Russian Scientific Conf. (4—5.12.2014). Yekaterinburg, 2014. Vol. 2. P. 333—335. (In Russ.).

   Чунарев А.А., Колмачихина О.Б., Набойченко С.С. Обзор методов переработки окисленных никелевых руд и перспективы развития на Урале никелевого производства. В сб.: *Урал индустриальный. Бакунинские чтения: Индустриальная модернизация Урала в XVIII–XXI вв.:* Материалы XII Всероссийской научной конференции (4—5 дек. 2014 г.). Екатеринбург, 2014. Т. 2. С. 333—335.

5. Kolmachikhina, O.B. Combined technology for processing oxidized nickel ores (on the example of the serovskoye deposit): Diss. ... Cand. Sci. (Eng.). Yekaterinburg, UrFU, 2018. (In Russ.).

   Колмачихина О.Б. Комбинированная технология переработки окисленных никелевых руд (на примере Серовского месторождения): Дис. ...канд. техн. наук. Екатеринбург: УрФУ, 2018. 132 с.

6. Andreev A.A., Dyachenko A.N., Kraydenko R.I. Processing of oxidized nickel ores using ammonium chloride. *Khimicheskaya tekhnologiya*. 2010;11(2): 91—96. (In Russ.).

   Андреев А.А., Дьяченко А.Н., Крайденко Р.И. Переработка окисленных никелевых руд с применением хлорида аммония. *Химическая технология*. 2010;11(2): 91—96.

7. Andreev A.A., Dyachenko A.N., Kraydenko R.I. Chlorammonium technology of processing oxidized nickel ores. *Tsvetnye metally*. 2011;1:18—21.

   Андреев А.А., Дьяченко А.Н., Крайденко Р.И. Хлораммонийная технология переработки окисленных никелевых руд. *Цветные металлы*. 2011;1:18—21.

8. Dudareva G.N., Irinchinova N.V., Dudarev V.I. Adsorption extraction of nickel (II) from aqueous solutions of technogenic character. *Izvestiya vuzov. Prikladnaya khimiya i biotechnologiya*. 2020;1(32):133—139. (In Russ.).
   https://doi.org/10.21285/2227-2925-2020-10-1-133-139

   Дударева Г.Н., Иринчинова Н.В., Дударев В.И. Адсорбционное извлечение никеля (II) из водных растворов техногенного характера. *Известия вузов. Прикладная химия и биотехнология*. 2020;1(32):133—139.
   https://doi.org/10.21285/2227-2925-2020-10-1-133-139

9. Kurdyumov V.R., Timofeev K.L., Maletsev G.I., Lebed A.B. Sorption extraction of nickel (II) and manganese (II) ions from aqueous solutions. *Zapiski Gornogo instituta*. 2020;242:209. (In Russ.).
   https://doi.org/10.31897/pmi.2020.2.209

   Курдюмов В.Р., Тимофеев К.Л., Мальцев Г.И., Лебедь А.Б. Сорбционное извлечение ионов никеля (II) и марганца (II) из водных растворов. *Записки Горного института*. 2020;242:209.
   https://doi.org/10.31897/pmi.2020.2.209

10. Tamjidi S., Esmaeili H., Moghadas B.K. Application of magnetic adsorbents for removal of heavy metals from wastewater: a review study. *Materials Research Express*. 2019;6(10):862—873.
    https://doi.org/10.1088/2053-1591/ab3ffb

11. Çelebi H., Gök G., Gök O. Adsorption capability of brewed tea waste in waters containing toxic lead (II), cadmium (II), nickel (II), and zinc (II) heavy metal ions. *Scientific Reports*. 2020;10(1):12.
    https://doi.org/10.1038/s41598-020-74553-4

12. Nilgün Onursal, Yalçın Altunkaynak, Ayşe Baran, Mehmet Can Dal. Adsorption of nickel (II) ions from aqueous solutions using Malatya clay: Equilibrium, kinetic, and thermodynamic studies. *Environmental Progress & Sustainable Energy*.2017;42(5):14150.
    https://doi.org/10.1002/ep.14150

13. Olufemi B., Eniodunmo O., Adsorption of nickel (II) ions from aqueous solution using banana peel and coconut shell. *International Journal of Technology*. 2018;9(3):434—445.
    https://doi.org/10.14716/ijtech.v9i3.1936

14. Chang Y.S., Au P.I., Mubarak N.M., Khalid M., Jagadish P., Walvekar R., Abdullah E.C. Adsorption of Cu(II) and Ni(II) ions from wastewater onto bentonite and bentonite/GO composite. *Environmental Science and Pollution Research*. 2020;27:33270—33296.
    https://doi.org/10.1007/s11356-020-09423-7

15. Khan M.I., Almesfer M.K., Danish M., Ali I.H., Shoukry H., Patel R., Gardy J., Nizami A.S., Rehan M. Potential of Saudi natural clay as an effective adsorbent in heavy metals removal from wastewater. *Desalination and Water Treatment*. 2019;158:140—151.
    https://doi.org/10.5004/dwt.2019.24270

16. Gupta S., Sharma S.K., Kumar A. Biosorption of Ni(II) ions from aqueous solution using modified Aloe barbadensis Miller leaf powder. *Water Science and Engineering*. 2019;12:27—36.
    https://doi.org/10.1016/j.wse.2019.04.003

17. Islam M.A., Awual M.R., Angove M.J. A review on nickel (II) adsorption in single and binary component sys-

tems and future path. *Journal of Environmental Chemical Engineering.* 2019;7(5):103305. https://doi.org/10.1016/j.jece.2019.103305

18. Shahat A., Hassan M.A. H., El-Shahat M.F., Osama El-Shahawy, Md. Rabiul Awual. Visual nickel (II) ions treatment in petroleum samples using a mesoporous composite adsorbent. *Chemical Engineering Journal.* 2018;334:957—967. https://doi.org/10.1016/j.cej.2017.10.105
19. Praveen P., Munilakshmi N., Sravani P. Removal of nickel (II) ion from an aqueous solution using red brick as an adsorbent. *Journal of Solid Waste Technology and Management.* 2023;49(2):175—184. https://doi.org/10.5276/jswtm/iswmaw/492/2023.175
20. Mahmoud O. Abd El-Magied, Ali M.A. Hassan, Hamdi M.H. Gad T.M. Removal of nickel (II) ions from aqueous solutions using modified activated carbon: A kinetic and equilibrium study. *Journal of Dispersion Science and Technology.* 2018;39(6). https://doi.org/10.1080/01932691.2017.1402337
21. Qasem N.A., Mohammed R.H., Lawal D.U. Removal of heavy metal ions from wastewater: A comprehensive and critical review. *npj Clean Water.* 2021;4(1):1—15. https://doi.org/10.1038/s41545-021-00127-0
22. Leonov S.B., Domracheva V.A., Elshin V.V., Dudarev V.I., Oznobikhin L.M., Randin O.I. Carbon sorbents based on fossil coals. Irkutsk: Irkutsk State Technical University, 2000. 268 p. (In Russ.).
    Леонов С.Б., Домрачева В.А., Елшин В.В., Дударев В.И., Ознобихин Л.М., Рандин О.И. Углеродные сорбенты на основе ископаемых углей. Иркутск: ИрГТУ, 2000. 268 с.
23. Leonov S.B., Elshin V.V., Dudarev V.I., Domracheva V.A. Method of Sorbent Production: Patent 2064335 (RF). 1996. (In Russ.).
    Леонов С.Б., Елшин В.В., Дударев В.И., Домрачева В.А. Способ получения сорбента: Патент 2064335 (РФ). 1996.
24. Dudareva G.N., Randin O.I., Petukhova G.A., Vakul'skaya T.I. On the mechanism of sorption of nickel (II) ions by modified carbon sorbents. *Protection of Metals and Physical Chemistry of Surfaces.* 2015;51(6):939—943. https://doi.org/10.1134/S2070205115060064
25. Dudareva G.N., Irinchinova N.V., Dudarev V.I., Petukhova G.A. Study of removal of nickel(II) from aqueous solutions by sorption. *Protection of Metals and Physical Chemistry of Surfaces.* 2019;55(5):841—848. https://doi.org/10.1134/S2070205119050071
26. Dudareva G.N. Sorption concentration and analytical determination of nickel: Monograph. Irkutsk: IRNITU, 2015. 154 p. (In Russ.).
    Дударева Г.Н. Сорбционное концентрирование и аналитическое определение никеля: Монография. Иркутск: ИРНИТУ, 2015. 154 с.
27. Marochkina V.V., Bueva E.I., Kulagina E.S. Comparative analysis of methods for determining chromium, vanadium, copper, nickel, manganese in steels and cast irons by the method of atomic absorption spectrometry with atomization in the flame. *Zavodskaya laboratoriya. Diagnostika materialov.* 2023; 89(2):57—63. (In Russ.). https://doi.org/10.26896/1028-6861-2023-89-2-II-57-64
    Марочкина В.В., Буева Е.И., Кулагина Е.С. Сравнительный анализ методик определения хрома, ванадия, меди, никеля, марганца в сталях и чугунах методом атомно-абсорбционной спектрометрии с атомизацией в пламени. *Заводская лаборатория. Диагностика материалов.* 2023;89(2):57—63. https://doi.org/10.26896/1028-6861-2023-89-2-II-57-64
28. Frolov Yu.G. Course of the colloid chemistry. Surface phenomena and disperse systems. Moscow: Khimiya, 1989. 462 p. (In Russ.).
    Фролов Ю.Г. Курс коллоидной химии. Поверхностные явления и дисперсные системы. М.: Химия, 1989. 462 с.
29. Tsivadze A.Yu., RusanovA.I., Fomkin A.A.,Voloshchuk A.M., Tovbin Y.K., Tolmachev A.M., Avramenko V.A. Physical chemistry of adsorption phenomena. Moscow: Granitsa, 2011. 302 p. (In Russ.).
    Цивадзе А.Ю., Русанов А.И., Фомкин А.А., Волощук А.М., Товбин Ю.К., Толмачев А.М., Авраменко В.А. Физическая химия адсорбционных явлений. М.: Граница, 2011. 302 с.

Information about the authors

Vladimir I. Dudarev – Dr. Sci. (Eng.), Professor of the Department of Chemistry and Biotechnology named after Prof. V.V. Tuturina, Irkutsk National Research Technical University (INRTU).
https://orcid.org/0009-0001-6477-4422
E -mail: vdudarev@mail.ru

Galina N. Dudareva – Cand. Sci. (Chem.), Associate Professor of the Department of Chemistry and Biotechnology named after Prof. V.V. Tuturina, INRTU.
https://orcid.org/0009-0004-3234-0672
E-mail: gndudareva@mail.ru

Ariadna A. Yakovleva – Dr. Sci. (Eng.), Professor of the Department of Chemistry and Biotechnology named after Prof. V.V. Tuturina, INRTU.
https://orcid.org/0000-0002-5747-2864
E-mail: ayakovistu@mail.ru

Информация об авторах

Владимир Иванович Дударев – д.т.н., профессор кафедры химии и биотехнологии им. проф. В.В. Тутуриной, Иркутский национальный исследовательский технический университет (ИРНИТУ).
https://orcid.org/0009-0001-6477-4422
E -mail: vdudarev@mail.ru

Галина Николаевна Дударева – к.х.н., доцент кафедры химии и биотехнологии им. проф. В.В. Тутуриной, ИРНИТУ.
https://orcid.org/0009-0004-3234-0672
E -mail: gndudareva@mail.ru

Ариадна Алексеевна Яковлева – д.т.н., профессор кафедры химии и биотехнологии им. проф. В.В. Тутуриной, ИРНИТУ.
https://orcid.org/0000-0002-5747-2864
E -mail: ayakovistu@mail.ru

Contribution of the authors

V.I. Dudarev – developed of the main concept, set the goal and objectives of the study, prepared the text, and formulated the conclusions.

G.N. Dudareva – performed calculations, tested samples, and prepared the text of the article.

A.A. Yakovleva – provided scientific guidance, revised the text, and refined the conclusions.

Вклад авторов

В.И. Дударев – формирование основной концепции, постановка цели и задачи исследования, подготовка текста, формулировка выводов.

Г.Н. Дударева – осуществление расчетов, проведение испытаний образцов, подготовка текста статьи.

А.А. Яковлева – научное руководство, корректировка текста, корректировка выводов.

The article was submitted 05.01.2024, revised 14.03.2024, accepted for publication 18.03.2024

Статья поступила в редакцию 05.01.2024 г., доработана 14.03.2024 г., подписана в печать 18.03.2024 г.