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Determination of Optimal Process Modes of Producing Manganese Alloys from Low-Grade Carbonate and Oxide Ores in Jet-Emulsion Unit

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Abstract—The paper presents the results of developing and testing a new resource-saving technology of processing low-grade oxide and carbonate manganese ores in a jet-emulsion unit. The basic principles of creating a jet unit and the technology of processing fine manganese ores are considered. A reducing gas, which is a product of implementing the manganese reduction technology in the jet-emulsion unit, is proposed as the means of the preliminary reduction of manganese from higher-grade oxides or decomposition of carbonates as well as for removing moisture from the ore. Thus, it is proposed to close the process, that is, create a consistent flow of matter and energy passing through the main jet-emulsion unit and the preparatory unit of the fluidized bed. The main task of designing the proposed technology is to determine the consumption of crude ore in the fluidized bed unit to obtain a given yield of the intermediate product and, at the same time, ensure the possibility of completely converting higher oxides or crude ore carbonates to low oxides with the help of the reducing gas produced in the main unit. To solve this problem, an optimization task is set and implemented. The first stage is the selection of a composition and consumption of the reducing gas and determination of the consumption of the original manganese ore, which ensures the output of a preset amount of intermediate product. The second stage is the optimization of the output and composition of the gas that should ensure the reduction process in the second unit. The paper presents the results of designing the technology of processing in the jet-emulsion unit for the oxide ore of the Selezen'skoe deposit and the carbonate ore of the Usinskoe deposits. A comparative analysis of the processing of manganese ores by the proposed technology and by the technology without preliminary reduction and roasting is made. The proposed technology of processing manganese ores in a closed-cycle jet-emulsion unit allows significantly reducing the specific costs of materials, increase productivity, and significantly reduces the energy intensity of the process compared to the processing of low-grade manganese ores without preliminary reduction or roasting.

Keywords: jet-emulsion unit, low-grade fine manganese ore, manganese reduction, resource-saving technology

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INTRODUCTION

Ferromanganese is currently produced mainly in shaft ore-smelting furnaces. These technologies have been mastered fairly well [1–3] but they are energy-intensive. It is fairly difficult to ensure a high reduction of manganese from relatively low-grade ores due to the high costs of their enrichment, with the carbonate ore processing technology being especially expensive [4–8]. It is therefore proposed to produce ferromanganese and manganese alloys directly from pulverized and fine materials in a jet-emulsion type unit (JEU) [9, 10]. This technology is aimed primarily at processing carbonate ores and pulverized oxidized concentrates [11, 12]. The continuous jet-emulsion metallurgical process is based on the principles of synergy and nonequilibrium thermodynamics, which has allowed creating the theoretical basis of the process and the universal design of the unit, in which various processes and technologies can be implemented [9–18].

The basic principles underlying the jet-emulsion process are formulated as follows: create a large reaction surface in the reaction chamber with the subsequent organization of a forced pressurized flow of the formed gas suspension; use the gas dynamic blocking of the exit passage; create a nonequilibrium stationary oscillatory mode at a given pressure level; and ensure the lower feeding of the two-phase air-fuel mixture formed in the reaction chamber into the vertical column reactor [11, 12].

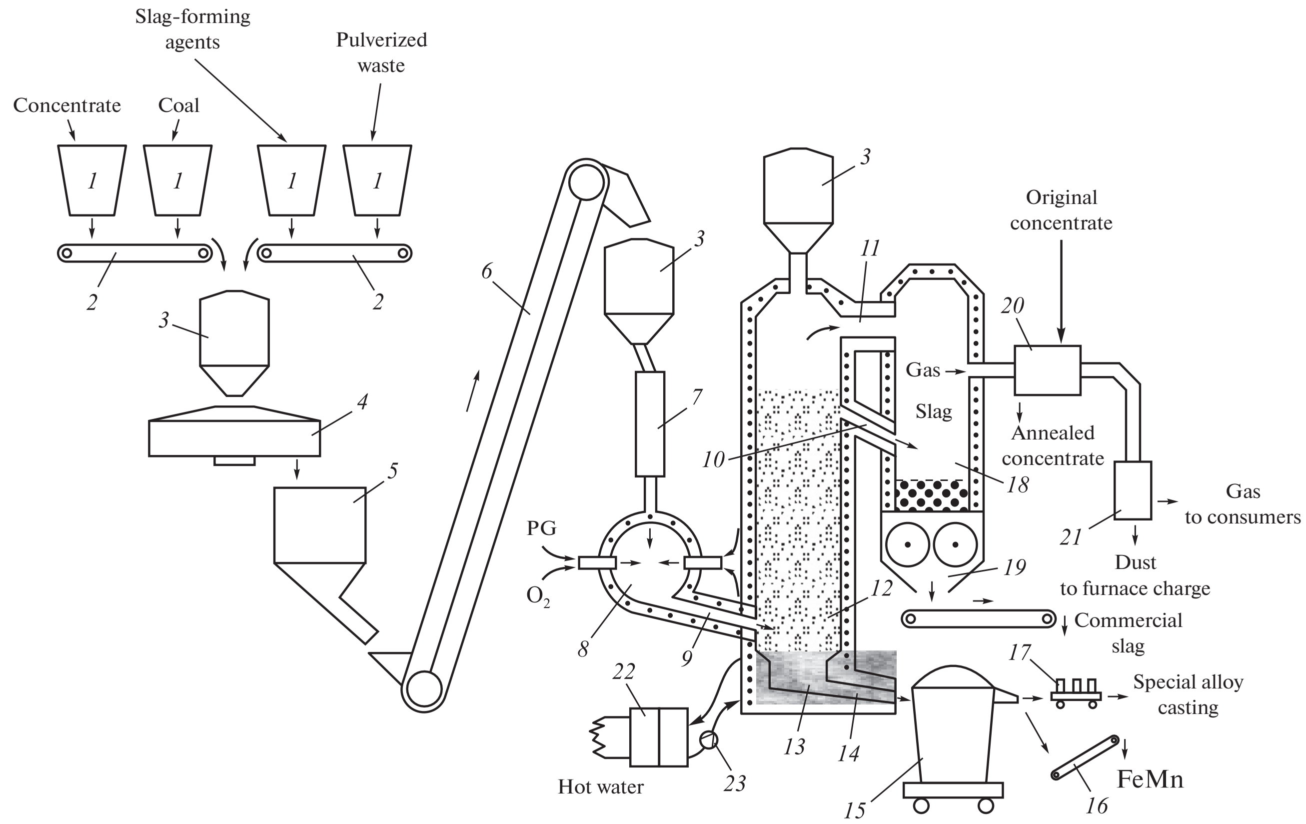

Fig. 1. Fine manganese concentrate processing flowchart: (*1*) the working hoppers; (*2*) the feeders; (*3*) the dispensers; (*4*) the mixer; (*5*) the feeding hopper; (*6*) the box conveyor; (*7*) the screw feeder; (*8*) the oscillating jet reactor; (*9–11*) the connective channels; (*12*) the column refining settler; (*13*) the induction-heated forehearth; (*14*) the taphole for metal; (*15*)s the receiving ladle or Presspour induction furnace; (*16*) the filling machine; (*17*) the special casting line; (*18*) the slag receiver; (*19*) the highly porous slag grainer; (*20*) the concentrate drying, roasting and pre-reduction unit; (*21*) the gas washing bottle; (*22*) the heat exchanger; (*23*) the circulation pump; and NG is natural gas.

These principles were used to switch from the system of spatially divided metal, slag, and gas to the biphase medium flow structured as a system of a huge amount of microreactors, where metal, slag, and gas are present in commensurate mass proportions. This ensure high rates of heat and mass exchange, oxidative reduction reactions, and phase transformations [11, 12].

MANGANESE ORE PROCESSING TECHNOLOGY

The flowchart of processing fine manganese ores in the jet-emulsion unit is shown in Fig. 1. Furnace charge materials, such as manganese concentrate, coal, pulverized waste, slag-forming agents, are supplied from the furnace charge preparation system to service hoppers *1*, from which these materials enter mixer *4* through feeders *2* and dispenser *3* and then fed under pressure to oscillating reactor *8* of the jet-emulsion unit through feeding hopper *5*, box conveyor *6* and screw feeder *7*. In the oscillating reactor, the furnace charge is dispersed and the fuel incompletely burned to CO at the interaction of countercurrents of oxygen [11, 12]. The gas suspension made in this reactor is supplied though gas-dynamically blocked connective channel *9* to the lower part of column reactor *12* under a high layer of gas-slag emulsion. The reactor is used to gasify and afterburn bigger solid fuel particles and reduce oxides.

Induction-heated fore-hearth *13* is connected to the lower part of the column reactor, in which iron, manganese and other metals reduced from oxides are accumulated. The depleted and heavily foamed slag is pushed out under pressure from the upper part of the column reactor through connection passage *10* to slag catcher *18* with grainer *19*. The produced slag is used as a building material, adsorbing matter, or as other materials.

The reaction gas consists mainly from carbon oxide and is a highly efficient reducer. This gas is supplied under pressure from the upper part of the slag catcher, that also plays the role or the gas/slag separator, to fluidized bed *20* with manganese concentrate for the pre-

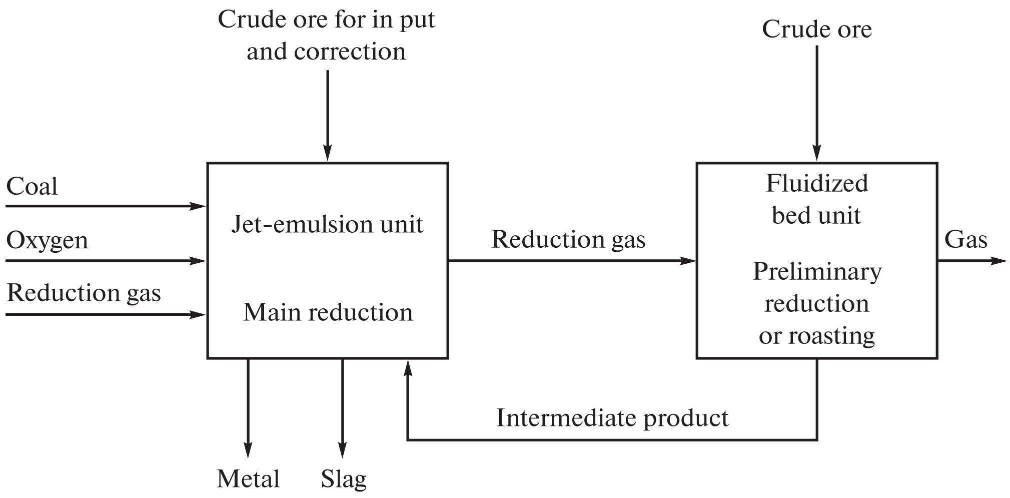

Fig. 2. Manganese ore processing chart.

liminary reduction of oxide concentrate to MnO or roasting carbonate concentrate. The pretreatment of manganese concentrate using the reducing gas from the jet-emulsion unit allows dramatically reducing the energy intensity of ferromanganese production [9].

The iron and manganese reduced in column reactor *12* are collected in induction-heated fore-hearth *13* and discharged (continuously or periodically) through taphole *14* into ladle or induction furnace *15*, where the metal composition is averaged and, in case of implementing the manganese steel production technology, the metal is refined to the specified composition. This metal can be used to produce special cast items, such as wear-resistant parts [12]. The durability of the unit's elements is ensured by an automated system of forming and maintaining wall accretion. This system consists from high-pressure heat exchangers *22* and control and monitoring parts [9]. Figure 1 also shows connecting channel *11*, filling machine *16*, special casting line *17*, gas washing bottle *21*, and circulating pump *23*.

The considered technology can be applied for processing manganese concentrates, for example, at the Selezenskoe deposit in the Kemerovo oblast, especially for processing low-grade dust fractions (14–24% Mn), which constitute almost half of all of the fractions in these concentrates. This will make it possible to reduce the amount of tails, increase the degree of manganese reduction and prolong the deposit's life.

SOLUTION OF THE OPTIMIZATION TASK

To preliminarily reduce manganese and remove moisture from the ore, it is proposed to use the reduction gas, that is produced by the reduction of manganese in the jet-emulsion unit, and thus close the process, that is, generate a combined flow of matter and energy running through the main and the preparatory (ancillary) unit [11, 12]. The flowchart of the flows of matter and energy for the proposed technology is shown in Fig. 2.

The main task of designing the proposed technology was to determine the crude ore consumption in the fluidized bed unit, that would be enough for making a preset intermediate product output (the intermediate product output accepted in the calculations is 1 kg/s) and, at the same time, allow fully converting high oxides or crude ore carbonates to low-grade oxides with the help of the reduction gas produced in the main unit [11, 12]. To solve this issue, the optimization task was set and implemented. The first stage was confined to selecting the composition and consumption of the reduction gas necessary for the full reduction of higher manganese oxides or decomposing carbonates and to calculating the consumption of the original manganese ore that ensured the output of a preset amount of product [11, 12].

At this productivity, the process in the main jet-emulsion unit was designed and the composition of the products determined. The task solved was the optimization of the output and composition of the gas that was intended to ensure the reduction process in the second unit. The coal and oxygen consumption levels, that were determined, were such at which the composition of the exit gas corresponded to the necessary composition on the assumption that the limitations on the conditions of the material and thermal balance at a preset temperature and on the conditions of implementing the reduction process at a preset reduction degree of iron and manganese were fulfilled. A calculation was made with the help of a tooling system for the considered technology of processing manganese ores in the jet-emulsion unit by the example of the manganese oxide ore of the Selezen'skoe deposit and manganese carbonate ore of the Usinkoe deposit [11, 12].

Table 1. Material balance of the technology of processing the ores of the Selezen'skoe deposit

Inbound flows	kg/s	%
Intermediate product	1.000	47.94
Coal	0.477	22.84
Silicon manganese (waste)	0.050	2.40
Oxygen	0.508	24.42
Natural gas	0.050	2.40
Materials consumption	2.085	100.00
Output flows		
Metal	0.448	21.48
Slag	0.566	27.05
Gas	1.071	51.47
Product output	2.085	100.00

Table 2. Thermal balance of the technology of processing the ores of the Selezen'skoe deposit

Gain	kJ/s	GJ/t
Exothermal reaction heat	5540.6	12.364
Inducer heat	1500.0	3.348
Total	7040.6	15.712
Consumption		
Metal heat	657.9	1.468
Slag heat	620.9	1.386
Gas heat	2645.4	5.904
Endothermal reaction heat	2516.4	5.615
Heat losses	600.0	1.339
Total	7040.6	15.712

DESIGN OF THE TECHNOLOGY OF PROCESS ORES OF THE SELEZEN'SKOE DEPOSIT

The fine (2.5–8.0 mm) manganese ore of the Selezen'skoe deposit [19] has the following chemical composition, wt %: 0.10 wt % of S, 0.33 wt % of MgO, 3.00 wt % of BaO, 0.05 wt % of Cu, 0.05 wt % of Zn, 0.01 wt % of Pb, and 8.20 wt % of MLI.

Since most of the manganese contained in the ore is oxide MnO_2, it is proposed to convert it to low oxide MnO in the fluidized bed unit using the reduction gas that is a product of the reduction of manganese in the main jet-emulsion unit. The design consumption of the gas is 1.074 kg/s. The chemical composition of the gas, wt %, is as follows: 87.69 wt % of CO, 0.62 wt % of CO_2, 0.75 wt % of N_2, 2.01 wt % of H_2, and 8.93 wt % of H_2O.

The oxidized ore consumption necessary for making a kilogram of the intermediate product was calculated by solving the optimization task and amounted to 1.26 kg.

After the preliminary reduction of the original ore in the fluidized bed unit, a semi-product is obtained and fed to the first reactor of the main jet-emulsion unit, where the oxides of manganese and iron are reduced. The material and heat balances of the process are given in Tables 1 and 2. The composition of the manganese alloy, wt%, produced by the technology is as follows: 29.37wt% of Fe, 3.00 wt % of C, 66.17 wt % of Mn, and 1.42 wt % of Si.

DESIGN OF THE TECHNOLOGY OF PROCESSING THE ORE OF THE USINSKOE DEPOSIT

A distinctive feature of carbonate manganese ores is the variety of mineral forms of manganese and grain sizing (from fractions of millimeters to several centimeters). The main ore minerals are manganese carbonates: rhodochrosite, manganocalcite, and manganiferous calcite. The manganese ore of the Usinkoe deposit has the following composition, wt %: 19.33 wt % of Mn, 0.18 wt % of P, 5.96 wt % of Fe, 16.33 wt % of SiO_2, 1.67 wt % of Al_2O_3, 14.84 wt % of CaO, 3.17 wt % of MgO, 0.06 wt % of S, and 24.98 wt % of MLI.

The results of studying the reduction of carbonate manganese ore by coal in the tooling system [7, 8] are shown in Fig. 3. The calculation is made for 1 kg of manganese ore. The best conditions for reducing manganese correspond to a coal consumption of 0.40–0.45 kg. In these conditions, the reduced manganese content is 60% and the reduced manganese oxide content is 8 to 12%. The gas phase consists from CO (90%), vaporized manganese (6%), and hydrogen (4%). The reduction is possible at a large excess (10–12%) of carbon in the system.

The technology of making manganese alloy from the ore of the Usinskoe deposit is similar to the previously considered technology of processing the ore of the Selezen'skoe deposit. The difference is that most of the compounds in the Usinkoe deposit ore are carbonates. It is proposed to decompose them using the reduction gas that flows from the main jet-emulsion unit and contains 89.58 wt % of CO, 0.63 wt % of CO_2, 0.76 wt % of N_2, 2.26 wt % of H_2, and 6.78 wt % of H_2O. The gas consumption was 1.099 kg/s.

The product resulting after preliminary reduction is the intermediate product then supplied for final processing to the main jet-emulsion unit. The carbonate ore consumption necessary for making a kilogram of the intermediate product was 1.406 kg/s. The material and thermal balances of this process are shown in Tables 3 and 4. The fractions of the elements in the composition of the final product are 18.33 wt % of Fe, 3.00 wt % of C, 77.47 wt % of Mn, and 1.16 wt % of Si.

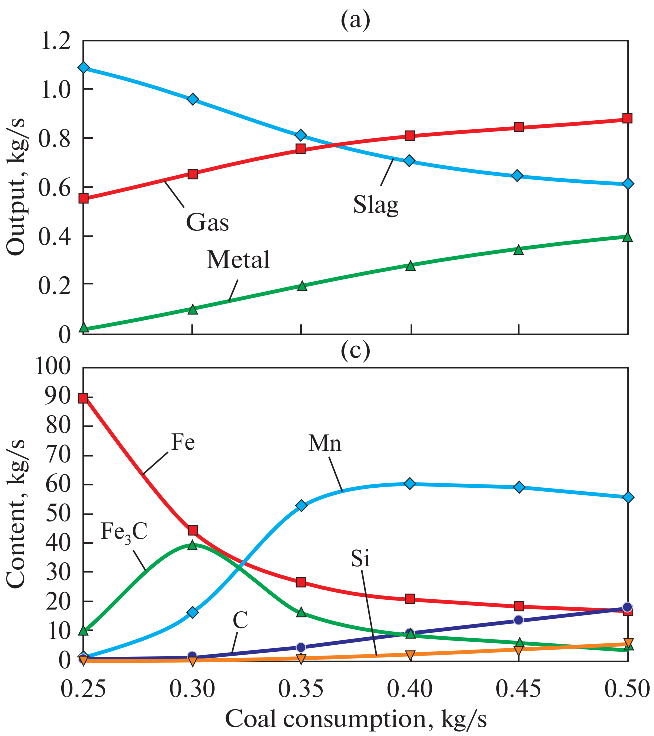

Fig. 3. Dependences of the parameters of reducing manganese recovery the manganese ore of the Usinskoe deposit on coal consumption.

COMPARATIVE ANALYSIS OF TECHNOLOGIES

The results of designing the technology with preroasting also showed a significant improvement in the performance indicators compared to the roasting-free technology: the productivity increased by 0.12 kg/s, the specific consumption of coal and oxygen were reduced by twofold, the energy intensity of the process was reduced by almost twofold (Table 5).

The comparative energy intensity analysis of the processing of manganese ore in the JEU with the traditional processing in the ore-smelting furnace [3] is presented in Table 6.

Table 3. Material balance of the technology of processing the ores of the Usinskoe deposit

Inbound flows	kg/s	%
Intermediate product	1.000	43.37
Coal	0.531	23.03
Silicon manganese (waste)	0.050	2.17
Lime	0.098	4.25
Oxygen	0.577	25.03
Natural gas	0.050	2.17
Materials consumption	2.306	100.00
Output flows		
Metal	0.365	15.83
Slag	0.770	33.39
Gas	1.171	50.78
Product output	2.306	100.00

Table 4. Thermal balance of the technology of processing the ores of the Usinskoe deposit

Gain	kJ/s	GJ/t
Exothermal reaction heat	5412.4	14.823
Inducer heat	1500.0	4.108
Total	6912.4	18.931
Consumption		
Metal heat	545.2	1.493
Slag heat	902.1	2.471
Gas heat	2728.3	7.472
Endothermal reaction heat	2136.8	5.852
Heat losses	600.0	1.643
Total	6912.4	18.931

Table 5. Comparative analysis of the indicators of the technology of processing manganese ores of the Selezens'koe and Usinskoe deposits

Indicator	Selezen'skoe deposit ore		Usinkoe deposit ore	
	with preliminary reduction	without preliminary reduction	with preliminary roasting	without preliminary roasting
Manganese ore, kg/t	2811.12	2969.04	3850.7	4062.20
Coal, kg/t	1063.42	2917.22	1363.82	2488.80
Silicon manganese (waste), kg/t	111.55	148.45	136.94	203.10
Oxygen, m^3/t	793.80	2184.30	1035.1	2012.60
Natural gas, m^3/t	151.99	202.27	186.58	276.70
Productivity, kg/s	0.45	0.34	0.37	0.25
Energy intensity, GJ/t	43.10	97.60	54.60	94.10
Manganese content, %	66.17	66.00	77.47	72.15

Table 6. Comparative analysis of the developed and the traditional manganese ore processing technologies

Technologies	Energy consumption, GJ/t of metal			
	roasting	caking	melting	total
	Traditional technology			
Melting in ore-smelting furnace (with 28.7% Mn as carbonate concentrate	5.1	13.4	72.0	90.5
	Processing in jet-emulsion unit			
Crude ore of the Usinskoe deposit (with 19% Mn)	Exit gas energy	–	54.6	54.6
Fine enriched ore of the Selezen'skoe deposit (with 24% Mn)	Exit gas energy	–	43.1	43.1

CONCLUSIONS

The proposed technology of treating manganese ores in a closed-cycle JEU makes it possible to significantly reduce the specific material consumption, increase the productivity and significantly reduce the energy intensity of the process as compared to the processing of low-grade manganese ores without preliminary reduction and roasting. The proposed technology of processing manganese ore in the jet-emulsion unit has a significant energy cost advantage compared to the traditional technology of melting ferromanganese in the ore-smelting furnace.

REFERENCES

1. Smirnov, L.A. and Tigunov, L.P., Manganese in its fatherland, *Met. Evrazii*, 1999, no. 6, pp. 20–23.
2. Emlin, B.I. and Gasik, M.I., *Spravochnik po elektrotermicheskim protsessam* (Handbook of Electrothermal Processes), Moscow: Metallurgiya, 1978.
3. Tolstoguzov, N.V., *Teoreticheskie osnovy i tekhnologiya plavki kremnistykh i margantsevykh splavov* (Theoretical Foundations and Technology of Melting of Siliceous and Manganese Alloys), Moscow: Metallurgiya, 1992.
4. Dedov, P.I. and Svitov, V.S., *Obogatitel'naya fabrika karbonatnykh margantsevykh rud* (Processing Plant of Carbonate Manganese Ores), Sverdlovsk: Uralmekhanobr, 2004.
5. Nokhrina, O.I., Rozhikhina, I.D., and Proshunin, I.E., *Poluchenie vysokokachestvennykh kontsentratov pri obogashchenii margantsevykh rud* (Obtaining High-Quality Concentrates during Manganese Ores Dressing), Novokuznetsk: Sib. Gos. Ind. Univ., 2019.
6. Litvintseva E.G., Tigunov L.P., Bronitskaya E.S., et al., *Development of effective methods of dressing and processing of oxidized and carbonate ores from Russian manganese deposits, Sostoyanie margantsevo-rudnoi bazy Rossii i voprosy obespecheniya promyshlennosti margantsem (State-of-the-Art of Russian Manganese Ore Base and Issues of Providing the Industry with Manganese), Krasnoyarsk*: Krasnoyarsk. Nauchn.-Issled. Inst. Geologii i Mineral'nogo Syr'ya, 2001, pp. 138–143.
7. Ding, P., Liu, Q.J., and Pang, W.H., A review of manganese ore beneficiation situation and development, *Appl. Mech. Mater.*, 2013, vol. 380-384, pp. 4431–4433. https://doi.org/10.4028/www.scientific.net/AMM.380-384.4431
8. Wang, Z., Yang, D., Yang, K., Guo, L., and Tan, J., A green enriching process of Mn from low grade ore of

manganese carbonate, *Appl. Mech. Mater.*, 2014, vols. 644–650, pp. 5427–5430. https://doi.org/10.4028/www.scientific.net/AMM.644-650.5427

9. Tsymbal, V.P., Kozhemyachenko, V.I., Rybenko, I.A., Padalko, A.G., and Olennikov, A.A., A new jet—emulsion metallurgical process, *Steel Transl.*, 2015, vol. 45, no. 8, pp. 550–554. https://doi.org/10.3103/S0967091215080173

10. Tsymbal, V.P., Kozhemyachenko, V.I., Rybenko, I.A., Mochalov, S.P., Padalko, A.G., Kalashnikov, S.N., Krasnoperov, S.Yu., Ermakova, L.A., and Olennikov, A.A., Background and principles of self-organizing jet-emulsion metallurgical unit, *IOP Conf. Ser.: Mater. Sci. Eng.*, 2016, vol. 150, p. 012018. https://doi.org/10.1088/1757-899X/150/1/012018

11. Rybenko, I.A., The optimization of the technologies in the jet-emulsive metallurgical plant with the use of the methodology and instrumented system of the simulation, *Chern. Metall. Byull. Nauchno-Tekh. Inf.*, 2017, no. 3, pp. 60–66.

12. Rybenko, I.A., Development of theoretical foundations and resource-saving technologies for direct reduction of metals using the method and instrumental system of modeling and optimization, *Extended Abstract of Doctoral (Eng.) Dissertation*, Novokuznetsk, 2018.

13. Nicolis, G. and Prigogine, I., *Self-Organization in Non-Equilibrium Systems*, New York: Wiley, 1977.

14. Haken, H., *Synergetics: An Introduction*, Berlin: Springer-Verlag, 1978.

15. Prigogine, I., Stengers, I., and Toffler, A., *Order Out of Chaos: Man's New Dialogue with Nature*, London: Heinemann, 1984.

16. Kondepudi, D. and Prigogine, I., *Modern Thermodynamics*, John Wiley & Sons, 2015.

17. Gladyshev, G.P., Hierarchical thermodynamics rules the world to the extent of its applicability, *Norw. J. Dev. Int. Sci.*, 2019, no. 27, pp. 60–65.

18. Tsymbal, V.P., Mochalov, S.P., Shakirov, K.M., Aizatulov, R.S., Kustov, B.A., Mikheev, N.I., and Toropov, A.I., Process and unit for continuous metal refinement, US Patent no. 5558695A, 1995.

19. Yashin V.D., Kolpak V.P., Dmitrienko V.I., et al., *Selezenskaya area of manganese ore manifestations and prospects for their use at JSC Zapsibmetkombinat, Sostoy, Sostoyanie margantsevo-rudnoi bazy Rossii i voprosy obespecheniya promyshlennosti margantsem* (State-of-the-Art of Russian Manganese Ore Base and Issues of Providing the Industry with Manganese), *Krasnoyarsk*: Krasnoyarsk. Nauchn.-Issled. Inst. Geologii i Mineral'nogo Syr'ya, 2001, pp. 44–45.

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