SEPARAÇÃO MAGNÉTICA SECA DE MINÉRIO DE MAGNETITA

DRY MAGNETIC SEPARATION OF MAGNETITE ORES

СУХАЯ МАГНИТНАЯ СЕПАРАЦИЯ МАГНЕТИТОВЫХ РУД

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RESUMO

A relevância do artigo reside no fato de que a separação magnética seca (SMS) é o principal método de enriquecimento de minérios de magnetita. A falta de máquinas e dispositivos industriais eficientes para separar os minérios de magnetita de granulação fina significa que a SMS é usada principalmente como uma operação de pré-concentração para as classes razoavelmente grandes. O objetivo do estudo é investigar a possibilidade de utilizar um novo modelo de separador magnético no processo de concentração a seco de minério de magnetita do depósito de Bapy. Este artigo apresenta os estudos teóricos e experimentais de um novo modelo de separador magnético. Foi realizada uma modelagem matemática do processo de separação magnética do dispositivo para avaliar os parâmetros de acordo com os quais o separador de laboratório foi posteriormente fabricado. Para o estudo experimental das propriedades desse sistema magnético, foi construído o separador magnético de laboratório. A possibilidade de usar o novo separador magnético no processo de beneficiamento a seco de minério de magnetita do depósito de Bapy foi investigada. O esquema industrial implementado consiste na esmagamento de minério e beneficiamento em dois estágios nos separadores magnéticos de tambor seco. O estudo dos indicadores de enriquecimento do separador magnético foi realizado utilizando o minério de ferro do depósito de Bapy, que é magnetita monomineral. Para o estudo, foram selecionadas as misturas da classe menos 0,1 mm com um teor de ferro de $\alpha = 50\%$ e $\alpha = 40\%$. Como resultado do estudo, foram obtidos os indicadores de enriquecimento em escala laboratorial. Assim, a melhoria do esquema de enriquecimento é reduzida ao isolamento de um produto pequeno e seu enriquecimento subsequente usando um novo modelo de separador magnético. Assim, o separador magnético apresentado é adequado para processamento a seco de minério de magnetita esmagado.

Palavras-chave: separador magnético, classificador pneumático, campo magnético do separador, suscetibilidade magnética de partículas, velocidade da correia.

ABSTRACT

The relevance of the paper is that dry magnetic separation (DMS) is the main beneficiation method of magnetite ores. The lack of efficient industrial-grade machines and apparatus for separating fine-grained magnetite ores means that DMS is used mainly as a pre-concentration operation for fairly large classes. The aim of the research is to study the possibility of using a new magnetic separator model in the process of dry beneficiation of magnetite ore from the Bapy deposit. This paper presents theoretical and experimental studies of a new model of a magnetic separator. The mathematical modeling of the magnetic separation process of the device was carried out to evaluate the parameters in accordance with which a laboratory separator was subsequently manufactured. For the experimental study of the properties of this magnetic system, a laboratory magnetic separator was built. The possibility of using a new magnetic separator in the process of dry beneficiation of magnetite ore from the Bapy deposit was investigated. The industrial scheme being implemented consists in ore crushing and two stage dressing on dry drum magnetic separators. The study of beneficiation indicators of the magnetic separator was carried out using iron ore of the Bapy deposit, which is mono-mineral magnetite. For the study, mixtures of the minus 0.1 mm class were selected with the iron content $\alpha = 50\%$ and $\alpha = 40\%$. As a result of the research, beneficiation indicators were obtained on a laboratory scale. Therefore, the improvement

of the beneficiation scheme is reduced to the isolation of a small product and its subsequent beneficiation using a new model of magnetic separator. Thus, the presented magnetic separator is suitable for dry processing of crushed magnetite ore.

Keywords: *magnetic separator, pneumatic louver classifier, magnetic field of the separator, magnetic susceptibility of particles, belt speed.*

АННОТАЦИЯ

Актуальность статьи заключается в том, что сухое магнитное разделение (СМС) является основным методом обогащения магнетитовых руд. Отсутствие эффективных промышленных машин и устройств для отделения мелкозернистых магнетитовых руд означает, что СМС используется в основном в качестве операции предварительного концентрирования для довольно больших классов. Целью исследования является изучение возможности использования новой модели магнитного сепаратора в процессе сухого обогащения магнетитовой руды месторождения Бапы. В данной статье представлены теоретические и экспериментальные исследования новой модели магнитного сепаратора. Математическое моделирование процесса магнитной сепарации устройства проводилось для оценки параметров, в соответствии с которыми впоследствии был изготовлен лабораторный сепаратор. Для экспериментального исследования свойств этой магнитной системы был построен лабораторный магнитный сепаратор. Исследована возможность использования нового магнитного сепаратора в процессе сухого обогащения магнетитовой руды с месторождения Бапы. Реализуемая промышленная схема состоит в дроблении руды и двухступенчатой обогащении на сухих барабанных магнитных сепараторах. Исследование показателей обогащения магнитного сепаратора проводилось с использованием железной руды месторождения Бапы, которая представляет собой мономинеральный магнетит. Для исследования были выбраны смеси класса минус 0,1 мм с содержанием железа $\alpha = 50\%$ и $\alpha = 40\%$. В результате исследования были получены показатели обогащения в лабораторном масштабе. Таким образом, усовершенствование схемы обогащения сводится к изоляции небольшого продукта и его последующему обогащению с использованием новой модели магнитного сепаратора. Таким образом, представленный магнитный сепаратор подходит для сухой переработки измельченной магнетитовой руды.

Ключевые слова: *магнитный сепаратор, пневматический классификатор, магнитное поле сепаратора, магнитная восприимчивость частиц, скорость ленты.*

1. INTRODUCTION

Dry magnetic separation (DMS) is the primary beneficiation method of magnetite ores, especially in places where water resources are scarce. Such is the situation at the Bapy ore deposit in Kazakhstan. The lack of efficient industrial-grade machines and apparatus for separating fine-grained magnetite ores means that DMS is used mainly as a pre-concentration operation for fairly large classes (Duman *et al.*, 2019; Chang and Cheng, 2019; Fan *et al.*, 2019; Eliopoulos and Economou-Eliopoulos, 2019). Thus, at the Bapy deposit, the -10mm grade ore is brought to an iron concentration of 52-54% by means of DMS, using traditional drum separators. This industrial product is the final commercial product. However, the iron content of the class of -0.3 mm drops to 42-46%. These results can be further improved by beneficiating individual finer classes. However, the use of traditional separators lowers the recovery of mineral particles (Karthaus *et al.*, 2019; D'Souza *et al.*, 2018; Zhang *et al.*, 2018).

A negative effect on the process of magnetic separation of small classes is exerted by the influence of a magnetic field on the behavior of particles, i.e., magnetic flocculation. The rotation of the magnetic field in the separators improves the situation and contributes to the destruction of magnetic agglomerations (Li *et al.*, 2015; Vorob'ev *et al.*, 2018; Zhao *et al.*, 2017a). It is possible to improve the current situation in DMS by improving the technology of dry magnetic beneficiation of crushed magnetite ores. Studies are underway in this direction (Urick, 2018; Edathil *et al.*, 2018; Tang *et al.*, 2020). It should be noted the development of work on the separation of magnetite ores in suspension (Sedinkina *et al.*, 2014; Yu *et al.*, 2017; Shahrokhi *et al.*, 2019).

In (Chokin *et al.*, 2012), a method was proposed where the finely ground material is loosened and crumbled into separate particles in a device for creating a dusty air mixture, and magnetic separation of particles is made from a dusty air mixture, which is blown at a constant speed into an inhomogeneous magnetic field and moves there along a path defined by a special

reflector, which ensures the movement of the dusty air mixture in the separation zone with the opposite action of centrifugal and magnetic forces (Kovalenker *et al.*, 2019; Kenzhaliev *et al.*, 2019). Particles having a magnetic susceptibility value above a certain value, depending on the ratio of these forces, are extracted from the overall flow into the magnetic product, and the residual dust-air mixture is removed from the separation zone. Traditionally, a magnetic separator is a magnetic system around which a non-magnetic drum rotates. Ore is fed from the top to a rotating non-magnetic drum and, due to centrifugal force, gangue particles bounce off the drum, and magnetic particles remain on it (Liu *et al.*, 2019; Liang *et al.*, 2019).

In (Chokin *et al.*, 2017), a new separator was proposed, the fundamental difference of which is that ore is fed into the magnetic field from the bottom along the inner surface of the carrier tape, which envelopes the drum and is separated from it by a certain distance. This gap is a separation area. Shredded ore is pressed to the belt centrifugally. Due to the magnetic force, magnetite particles detach from the surface of the carrier tape and are attracted to a rotating non-magnetic drum, and the waste remains on the tape. Thus, in the first case, beneficiation occurs due to the fact that non-magnetic particles leave the drum, and in the second, vice versa – the magnetic particles in the opposite direction leave the surface of the tape and are attracted to the rotating drum.

2. MATERIALS AND METHODS

In the present work, theoretical and experimental studies of this magnetic separator (Chokin *et al.*, 2017; Zhao *et al.*, 2017b) for dry beneficiation of magnetites are carried out. The beneficiation indices obtained on a model laboratory separator are obtained. The discussed method of magnetic separation of finely divided magnetic separation is shown schematically in Figure 1. The magnetic separator consists of: a movable drum of non-magnetic material “1”, a stationary magnetic system “2” installed inside it and consisting, for example, of permanent magnets with alternating polarity, a conveyor with a bearing surface “3”, which is a convex cylindrical surface with a generatrix parallel to the axis of the drum, a divider “4”, which separates the magnetic “5” and non-magnetic “6” fractions and the feeder tray “7”.

The device operates as follows. Bulk material is fed by the feeder “7” to the moving belt

of the conveyor “3” and moves it into the magnetic field. Centrifugal force presses the particles against the inner surface of the conveyor belt. In the separation zone, a magnetic force acts on the magnetic particle to counteract the centrifugal force. Magnetic particles are attracted by the magnetic field to the surface of the rotating drum “1”, moved by the drum to the zone of absence or significant weakening of the magnetic field, where they are separated from the surface of the drum, and non-magnetic particles remain on the moving conveyor belt and are transferred by it to the receiver for the non-magnetic fraction.

The proposed device for magnetic separation allows adjusting the selectivity of separation according to the magnetic properties of the particles. This is achieved by changing the centrifugal force acting on the particles, which counteracts the magnetic force of attraction. By changing the speed of movement of the reflector tape, it is possible to efficiently isolate the magnetic fraction of particles with a wide range of values of the magnetic susceptibility of the particles.

The study of beneficiation indicators of the magnetic separator was carried out using iron ore of the Bapy deposit, which is mono-mineral magnetite. The matrix components of the ores are diopside and serpentine. The mineralogical and petrographic analysis allows us to evaluate the effectiveness of magnetic separation (Parian *et al.*, 2016; Lund *et al.*, 2015; Li *et al.*, 2016a; Yu *et al.*, 2015). Such observations determined in diopside and serpentine the frequent presence of thin dispersed (pulverized) disseminated magnetite with sizes in the range of 1-5 microns. As a result, fine dusty particles of silicates, 10-50 microns in size, can stick together with the same but larger particles of magnetite, which to some extent, complicates magnetic separation, especially in the air. Magnetite grains, in this case, have a shell of weakly magnetic dust, in which the content of magnetite iron is much lower than in standard ores. Ore is difficult to process. With the wet magnetic separation of class minus 0.1 mm, the maximum iron content in the concentrate does not exceed 62%. The physical reason for the difficult beneficiation, apparently, is due to the fact that the proportion of grains in intergrowths in the class of -0.1 +0.071 mm is 27%, and in the class of -0.071 mm – 17%.

In (Sedinkina *et al.*, 2014), a mixture of magnetite and quartz was used to determine the beneficiation parameters of the magnetic separator in suspension. In the present work, due to the absence of magnetite, it was replaced with

concentrate with an average iron content of 60.6%. It was received as follows. At first, the initial ore was taken with a particle size of minus 10 mm with an average iron content of 54%. Then crushing and grinding were carried out to a class of -0.1 mm. The required amount of 60.6% Fe concentrate was obtained by preliminary magnetic separation of the crushed ore in the laboratory magnetic separator under study. After that, the mixture was prepared from the obtained concentrate and construction chamotte fines of the same class by thorough mixing (Li *et al.*, 2016b; Schlüter and Saboktakin, 2016). Unfortunately, in contrast to magnetic properties and density, such a mixture is inferior to a mixture using magnetite, which ultimately reduces the measured beneficiation indices. For the study, mixtures of the minus 0.1 mm class were selected with the iron content $\alpha = 50\%$ and $\alpha = 40\%$. The first option was used to assess the ability of the separator for dry beneficiation of the industrial fields of the Bapy deposit. The second mixture with $\alpha = 40\%$ expanded the measurement range. Table 1 shows the beneficiation at various speeds of the tape.

In line 1, beneficiation indicators correspond to a magnetic system with a full set of magnets. It can be seen that with an increase in the speed of the tape, the iron content β in the final product increases with some decrease in ε extraction. Note that β does not change at speeds greater than 7.6 m/s. Apparently, this is due to the fact that in the test mixture prepared from 60.6% Fe concentrate, magnetite splices have a rather high lower limit of the concentration of iron in the splices. Real ore has a set of splices with a wider difference in iron concentrations. Then, with an increase in velocity over 7.6 m/s, intergrowths with a low concentration of Fe will be cut off, and β will increase.

Rows 2 and 3 present the result of measuring the beneficiation indices for the magnetic system from which one magnet is removed. This option was theoretically considered earlier and is shown in fig. 2 and 3. A comparison of the indicators in lines 1 and 2 indicates that shaking the particles on the drum when passing through a region with a low magnetic field strength leads to some purification of the magnetic product. In this case, the extraction drops. The data obtained in the study of separation of the mixture with a particle size of -0.1 mm with increased content of gangue rock $\alpha=40\%$ (row 3) indicate a good extraction of the magnetic product. It, of course, falls in comparison with $\alpha=50\%$, but, nevertheless, remains quite high.

3. RESULTS AND DISCUSSION:

Mathematical modeling of particle motion in a magnetic field and experimental verification allows us to evaluate the effectiveness of the magnetic separator (Charikinya *et al.*, 2017; Thiagu and Dhanasekaran, 2014; Zhang *et al.*, 2020). For this purpose, authors consider the movement of particles in a space bounded by two cylindrical surfaces, namely, internal and external (Figure 1). If a particle has a certain specific magnetic susceptibility χ , and in a moving space, there is a magnetic field of intensity H , which weakens in the direction from the inner surface to the outer, then the motion of the particles will be quite complicated. The magnetic field will attract a particle of mass m with a magnetic force F_{mag} , as described in Equation 1.

$$F_{mag} = m\mu_0\chi H \text{ grad}H \quad (\text{Eq. 1})$$

where μ_0 is the magnetic constant, equal to $1.256 \cdot 10^{-6}$ H/m, χ is the specific magnetic susceptibility, m^3/kg . The direction of action of the force is determined by the gradient and, in this case, is directed from the surface of the tape towards the drum. Another force acting on the particle is the force of gravity, as in Equation 2.

$$F_g = mg \quad (\text{Eq. 2})$$

Where g is the acceleration of gravity, in this separator, the tape and non-magnetic drum rotate in the same direction with the same angular velocity. The small gap between them allows us to assume that the air layer in this gap also moves with the same angular velocity. In this case, authors can neglect the air resistance acting on the moving particle in this gap, because particle velocity relative to airflow will be negligible. The magnetic field of the separator is considered to be two-dimensional/cylindrical since the length of the magnetic system in the axial direction has a significant extension. Then, in the cylindrical coordinate system, the particle trajectory is a function of two coordinates: radius R and polar angle ϕ .

$$\begin{cases} \frac{d^2r}{dt^2} = F_r(r, \phi) + r\left(\frac{d\phi}{dt}\right)^2 - g\cos\phi \\ r\frac{d^2\phi}{dt^2} = F_\phi(r, \phi) + g\sin\phi - 2\frac{dr}{dt}\frac{d\phi}{dt} \end{cases} \quad (\text{Eq. 3})$$

Where $F_r(r, \phi)$ and $F_\phi(r, \phi)$ are the radial and angular projections of the specific magnetic force, respectively. Border conditions:

$$\frac{d\varphi}{dt} = -\omega_1, \text{ for } r = R_1; \quad (\text{Eq. 4})$$

$$\frac{d\varphi}{dt} = -\omega_2, \text{ for } r = R_2; \quad (\text{Eq. 5})$$

where R_1 is the radius of the rotating non-magnetic drum, R_2 is the radius of curvature of the tape:

$$R_1 \leq r \leq R_2 \quad (\text{Eq. 6})$$

Initial condition

$$t=0, \varphi=\pi;$$

$$r = R_2;$$

$$\frac{d\varphi}{dt} = -\omega_2 = -V/R_2. \quad (\text{Eq. 7})$$

The calculation is carried out to the condition $\varphi = 0$. The authors decided to elaborate on the calculation of the magnetic field. As previously noted, the field is considered cylindrical. It is convenient to calculate such a system under the assumption that, due to the high anisotropy constant, the rotation of the magnetization vector is impeded. Authors can assume that there are no space charges and that the source of the field is constituted only by surface charges located on the arcs of the circles of the pole ends. In (Tolmachev, 1974), a method for calculating such magnetic systems was described, which was applied in this paper.

The mathematical modeling of the magnetic separation process of the device, the scheme of which is shown in Figure 1, was carried out to evaluate the parameters in accordance with which a laboratory separator (Figure 4) was subsequently manufactured. It was initially assumed that the outer radius of the non-magnetic drum constitutes 100 mm, the radius of the arc of the circumference of the outer pole ends is 94.5 mm.

Used components from leading manufacturers (Nord, SKF), which have high-performance characteristics. It is made using both ferrite and modern high-energy Nd-Fe-B neodymium magnets, which ensures the value of magnetic induction on the drum surface in the range of 50-500 mT. In the manufacture of used stainless shell 6 mm thick of steel 12X18H10T, which can significantly increase its service life and operation. Three standard drum diameters are manufactured: 900, 1200, 1500 mm with a working zone length from 1000 mm to 3000 m. The cost of operation depends on the frequency of use, load, and type of magnetic separator.

The available Nd-Fe-B magnets were 15x20x80 mm with a residual magnetic induction of ~ 300 mT. The magnetic susceptibility of the mixture χ_{cp} depends on the concentration of magnetite in the intergrowths and the magnetic field strength. In accordance with (Karmazin *et al.*, 1999), the magnetic susceptibility at each point of the separated space was calculated using the formula:

$$\chi_{cp} = k_2 H^2 + k_1 H + k_0, \quad (\text{Eq. 8})$$

where k_2 , k_1 , k_0 are the coefficients, depend on the concentration of magnetite in the intergrowths α_m , and N is the local magnetic field strength. These calculations do not take into account the dependence of the magnetic susceptibility on the particle size, which is characteristic of small particles as a manifestation of the transition of a multi-domain structure to a single domain (Yurov, 2009; Bonyadi and Sadeghi, 2020; Cournède *et al.*, 2020). The mathematical modeling of the magnetic separation process is reduced to a system (3) of particle motion equations, which was solved numerically by the fourth-order Runge-Kutta method. Initial data: initial position (values of R and φ) of the particle at the inlet of the separator, iron concentration in intergrowths α , magnetite density 5 g/cm³ and empty rock 2.8 g/cm³. The initial particle velocity is equal to the speed of the tape. Next, the trajectory of the particle during the separation time is traced. Of interest is the case when several Nd-Fe-B magnets are replaced by a weaker magnet, for example, ferrite or one magnet, in general, is removed and a "dip" of the magnetic field is formed in its place. Figure 2 shows the radial component of the magnetic force acting on the particle when one Nd-Fe-B magnet is removed from the system. Figure 3 shows the calculated trajectories of the intergrowths of magnetite particles with $\alpha = 57\%$ Fe in the separation field (Figure 2) with different belt speeds.

Of particular interest in this calculation is the fact that the particles located on the magnetic drum and passing over the area with the missing magnet are detached from the drum, and then, upon falling into the region where the magnetic force increases, again gravitate to the drum. All particles in this area are shaken. If a non-magnetic particle enters the drum during the separation process and is held on top of the drum by a magnetic particle from above, then shaking releases particles of waste rock. They subsequently return to the tape. Thus, the

magnetic fraction is cleaned of waste rock particles that accidentally hit the drum.

For the experimental study of the properties of this magnetic system, a laboratory magnetic separator (Figure 4) was built with the parameters defined above. The operating mode of the magnetic separator is determined by the frequency of rotation of the non-magnetic drum in a magnetic field or, equivalently, the speed of the tape. This parameter affects the magnitude of the centrifugal force acting on the ore particles. In this geometry of the separator, the angular velocity of rotation of the non-magnetic drum was 3.5 times slower than the speed of the engine. The maximum engine speed was 2800 rpm, which corresponds to 780 rpm of rotation of a non-magnetic drum or 9.5 m/s belt speed.

The possibility of using a new magnetic separator in the process of dry beneficiation of magnetite ore from the Bapy deposit was investigated. The industrial scheme being implemented consists of ore crushing and two-stage dressing on dry drum magnetic separators. An industrial product with a grain size of -10 mm with an average iron content of 52-54% is shipped at the outlet. The lowest concentration of Fe has a small class. Therefore, the improvement of the enrichment scheme is reduced to the isolation of a small product and its subsequent enrichment using a new magnetic separator.

For the industrial selection of a small class, the application of the air classification method is technically and economically promising. For this purpose, a pneumatic louver classifier with reverse air suction was manufactured (Ponomarev, 2015; Sun *et al.*, 2020; Gahrouei *et al.*, 2020). The fractional separation of the intermediate product of the initial size -10 mm in the air classifier is shown in Figure 5.

The yield of a finer product with a size of approximately minus 300 μm was $\sim 14\%$. The total iron content $\beta = 54\%$. Moreover, in the large class – $\beta = 55.6\%$ Fe, and in the isolated small product, the iron concentration is much lower, only $\beta = 44\%$ Fe. The aim of the experiment was to raise the iron content in the fine product to 56%. In this case, the total iron content in the intermediate product will increase by about 2% without additional grinding operations and high financial costs. In a magnetic separation experiment, a 1 kg sample was used. Table 2 shows the data of the magnetic separation of the selected small product at different speeds of the tape.

It is notable that increasing the speed of the tape from 4 m/s to 9.5 m/s increases the average

concentration of iron in the magnetic product from 53.4% at 58%. Unfortunately, the speed of 9.5 m/s was the maximum speed of the tape in this geometry and the configuration of the magnetic separator. The purification of product No. 1, carried out at the same speeds, slightly increased the iron content in the concentrate from 53.4% to 55%. A similar conclusion can be made about the product obtained at 9.5 m/s when there is a change from 58% to 59.3%. Thus, the speed of the tape determines a certain upper limit of beneficiation. It should be noted that the cleaning of product No. 2 at a higher speed of the tape leads to content of $\beta = 59\%$ Fe in the final product, and the same operation performed at a higher speed of the tape of the first separation gives a slight increase in the final product $\beta = 59.3\%$ Fe. But in the first instance, the recovery ε was 92%, and in the second, it decreased slightly to 90.9% with comparable iron content.

4. CONCLUSIONS:

Thus, according to the optimal beneficiation scheme, in order to achieve higher beneficiation rates, it is desirable to carry out the process in two stages. At the first stage, beneficiation is carried out at a belt speed of 4-5 m/s, and the subsequent cleaning of the magnetic product of the first stage is carried out at an increased speed of 9-10 m/s. But to achieve the goal of 56% Fe, it is enough to carry out beneficiation in one stage at a belt speed of 8.4 m/s.

The possibility of using a new magnetic separator model in the process of dry beneficiation of magnetite ore from the Bapy deposit was studied. The industrial scheme being implemented consists of ore crushing and two-stage dressing on dry drum magnetic separators. An industrial product with a grain size of -10 mm with an average iron content of 52-54% is shipped at the outlet. Finer classes have the lowest Fe content. Therefore, the improvement of the beneficiation scheme is reduced to the isolation of a small product and its subsequent beneficiation using a new model of magnetic separator. Thus, the presented magnetic separator is suitable for dry processing of crushed magnetite ore. Note that the higher speed of the tape increases the performance of the device.

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6. REFERENCES:

1. Bonyadi, Z., Sadeghi, R. *Journal of Asian Earth Sciences*, **2020**, 189, Article number 104152.
2. Chang, Q., Cheng, X. *Chinese Journal of Environmental Engineering*, **2019**, 13(9), 2152-2163.
3. Charikinya, E., Robertson, J., Platts, A., Becker, M., Lamberg, P., Bradshaw, D. *Minerals Engineering*, **2017**, 107, 53-62.
4. Chokin, K.Sh., Edilbaev, A.I., Edilbaev, B.A., Yugay, V.D. Eurasian patent No. 025638. *Device and method for magnetic separation*, **2017**.
<https://www.eapo.org/ru/publications/bulletin/ea201701/HTML/025638.html>, accessed December 2019.
5. Chokin, K.Sh., Edilbaev, A.I., Yugay, V.D. Eurasian patent No. 016328. *The method of magnetic separation and device for its implementation*, **2012**.
<https://www.eapo.org/rus/bulletin/ea201204/HTML/016328.html>, accessed December 2019.
6. Cournède, C., Gattacceca, J., Rochette, P., Shuster, D.L. *Earth and Planetary Science Letters*, **2020**, 533, Article number 116042.
7. D'Souza, R., Vats, T., Chattree, A., Siril, P.F. *Renewable Energy*, **2018**, 126, 1064-1073.
8. Duman, F., Sahin, U., Atabani, A.E. *Fuel*, **2019**, 256, Article number 115935. DOI: 10.1016/j.fuel.2019.115935
9. Edathil, A.A., Shittu, I., Hisham Zain, J., Banat, F., Haija, M.A. *Journal of Environmental Chemical Engineering*, **2018**, 6(2), 2390-2400.
10. Eliopoulos, D.G., Economou-Eliopoulos, M. *Minerals*, **2019**, 9(12), Article number 759.
11. Fan, R., Min, H., Hong, X., Yi, Q., Liu, W., Zhang, Q., Luo, Z. *Journal of Hazardous Materials*, **2019**, 364, 780-790.
12. Gahrouei, Z.E., Labbaf, S., Kermanpur, A. *Physica E: Low-Dimensional Systems and Nanostructures*, **2020**, 116, Article number 113759.
13. Karmazin, V.V., Bikbov, M.A., Bikbov, A.A. *Mountain News and Analysis Bulletin*, **1999**, 4, 9-12.
14. Karthaus, J., Elfgen, S., Leuning, N., & Hameyer, K. *International Journal of Applied Electromagnetics and Mechanics*, **2019**, 59(1), 255-261.
15. Kenzhaliev, B.K., Kvyatkovskii, S.A., Kozhakhmetov, S.M., Sokolovskaya, L.V., Kenzhaliev, É.B., Semenova, A.S. *Metallurgist*, **2019**, 63(7-8), 759-765.
16. Kovalenker, V.A., Plotinskaya, O.Y., Kiseleva, G.D., Minervina, E.A., Borisovskii, S.E., Zhilicheva, O.M., Yazykova, Y.I. *Geology of Ore Deposits*, **2019**, 61(6), 559-579.
17. Li, L., Liu, T., Liu, X. 2015. *Mining Engineering*, **2015**, 13(6), 23-26.
18. Li, Q.-L., Han, L.-N., Chang, L.-P., Bao, W.-R., & Wang, J.-C. *Modern Chemical Industry*, **2016a**, 36(9), 28-31.
19. Li, Z., Lun, Q., Wang, Q., Zhang, L. *Journal of Harbin Institute of Technology*, **2016b**, 48(3), 33-38.
20. Liang, Z., Yi, L., Huang, Z., Lu, B., Jiang, X., Cai, W., Tian, B., Jin, Y. *Powder Technology*, **2019**, 356, 691-701.
21. Liu, D.-F., Shi, X.-J., Tang, C.-J., Cao, H.-P., Li, J. *Journal of Iron and Steel Research International*, **2019**, 26(11), 1154-1161.
22. Lund, C., Lamberg, P., Lindberg, T. *Minerals Engineering*, **2015**, 82, 61-77.
23. Parian, M., Lamberg, P., Rosenkranz, J., *International Journal of Mineral Processing*, **2016**, 154, 53-65.
24. Ponomarev, V.B. *Calculation and design of equipment for air separation of bulk materials*, Yekaterinburg: Ural Federal University, **2015**.
25. Schlüter, H., Saboktakin, M. *Journal of Pharmacy and Nutrition Sciences*, **2016**, 6(4), 126-143.
26. Sedinkina, N.A., Pavelin, A.V., Khisametdinova, D.N., Mubaryakov, R.S. *Actual Problems of Modern Science, Technology and Education*, **2014**, 1, 39-42.
27. Shahrokhi, B., Pirdashti, M., Managhebi, M. *Iranian Journal of Science and Technology, Transaction A: Science*, **2019**, 43(6), 2807-

2813.

28. Sun, Y., Zhang, X., Han, Y., Li, Y. *Powder Technology*, **2020**, 361, 571-580.
29. Tang, Z., Gao, P., Li, Y., Han, Y., Li, W., Butt, S., Zhang, Y. *Powder Technology*, **2020**, 361, 591-599.
30. Thiagu, G., Dhanasekaran, R. *Journal of Theoretical and Applied Information Technology*, **2014**, 64(2), 386-392.
31. Tolmachev, S.T. *University News. Electromechanics*, **1974**, 10, 1071-1076.
32. Urick, D. United States Patent Application No. 20180093279. *Magnetic separator apparatus*, **2018**. <http://appft1.uspto.gov/netacgi/nph-Parser?Sect1=PTO2&Sect2=HITOFF&p=1&u=%2Fnetacgi%2FPTO%2Fsearch-bool.html&r=2&f=G&l=50&co1=AND&d=PG01&s1=%22dry+magnetic+separator%22&s2=air&OS=%22dry+magnetic+separator%22+AND+air&RS=%22dry+magnetic+separator%22+AND+air>, accessed December 2019.
33. Vorob'ev, V.A., Ivanov, E.N., Larionov, A.N., Ryazanov, M.A. Dry technologies of ore preparation as a tool for increasing extraction of valuable components. In *XXIX International Mineral Processing Congress (IMPC 2018)* (pp. 708-715), Moscow: IMPC, **2018**.
34. Yu, L., Zhang, S., Zhang, M., Chen, J. *Applied Surface Science*, **2017**, 425, 46-55.
35. Yu, X., Zhang, Z.-L., Zheng, S.-Y. *Biosensors and Bioelectronics*, **2015**, 66, 520-526.
36. Yurov, V.M. *Modern Problems of Science and Education*, **2009**, 4, 152-155.
37. Zhang, T., Yuan, Y., Cui, X., Yin, H., Gu, J., Huang, H., Shu, J. *Journal of Polymer Science, Part B: Polymer Physics*, **2018**, 56(9), 751-761.
38. Zhang, X., Han, Y., Sun, Y., Lv, Y., Li, Y., Tang, Z. *Mineral Processing and Extractive Metallurgy Review*, **2020**, 41(2), 117-129.
39. Zhao, H.L., Wang, X.M., Wei, H.G. *Nonferrous Metals (Mineral Processing Section)*, **2017a**, 10(9), 87-89.
40. Zhao, Y., Wang, X., Liu, L., Liang, W. *Acta Materiae Compositae Sinica*, **2017b**, 34(1), 121-128.

Figure 1. Magnetic separator circuit

Figure 2. Radial component of magnetic force

Figure 3. The trajectories of the growths of magnetite particle aggregates with $\alpha_M = 57\%$ Fe in the separator field with different belt speeds V: 1 – 8.5 m/s; 2 – 9.5 m/s; 3 – 10.5 m/s

Figure 4. Laboratory magnetic separator: 1 - trunk, 2 - pulley, 3 - waste rock receiver, 4 - concentrate receiver, 5 - feeder, 6 - electric motor

Figure 5. The degree of fractional extraction into a fine product during air classification

Table 1. Beneficiation figures

No.	$\alpha, \%$	The speed of the tape, m/s											
		3,8			5,7			7,6			9.5		
		$\gamma, \%$	$\beta, \%$	$\epsilon, \%$	$\gamma, \%$	$\beta, \%$	$\epsilon, \%$	$\gamma, \%$	$\beta, \%$	$\epsilon, \%$	$\gamma, \%$	$\beta, \%$	$\epsilon, \%$
1	50	86.1	57.1	98.3	81.0	59.3	96.1	74.6	61.2	91.3	70.5	61.3	86.4
2	50	83.0	57.8	95.9	78.9	59.4	93.8	72.4	61.3	88.8	70.4	61.3	86.3
3	40	69.9	55.5	96.9	62.4	58.6	91.4	59.6	60.8	90.7	-	-	-

Table 2. Magnetic separation results at various belt speeds

No.	Belt speed, m/s	β	ϵ
1	4	53.4%	94.5%
Recycling No. 1	4	55.0%	93.6%
2	4.8	54.0%	94.2%
Recycling No. 2	9.5	59.0%	92.0%
3	7.6	55.7%	93.4%
4	9.5	58.0%	92.2%
Recycling No. 4	9.5	59.3%	90.9%