UDC Identifier 622.7:669.04 DOI: 10.21440/0536-1028-2018-7-67-74

SOME FEATURES OF MASS TRANSFER AT SPIRAL DEVICES

PROKOP'EV S. A.[1], PELEVIN A. E.[2], MOROZOV IU. P.[2]
[1] OOO Manufacturing Company Spirit
(Lermontova Str., 128/2, room 305, Irkutsk, the Russian Federation)
[2] The Ural State Mining University
(Kuibysheva Str., 30, Ekaterinburg, the Russian Federation)

Research aim *is to investigate the mechanism of mass transfer at spiral separators and to determine motive powers of particles stratification in a flow.*
Research methodology. *The issues of water flows and pulp mass transfer at spiral separators are considered. To assess the states and the flow modes, the Froude number and the Reynolds number were determined. It has been shown that water flows at spiral devices refer to complex fluid motion modes. They have no fixed depth and speed along the width of the trough. Within one trough, a water flow has several modes and states simultaneously, from laminar "smooth" and laminar "rough" to turbulent "rough".*
Results and analysis. *The presence of capillary and gravitational waves and transverse circulation of flows has been stated. Researches over the determination of circulations at spiral troughs have shown that the upper flows move along the unfolding spirals gradually approaching the outer side. Getting close to the bottom, the water currents move along the folding spirals with a decreasing radius.*
The presence of transverse circulation has been determined by experiment. When spiraling down along the trough, the water currents sink to the depth of a flow near the outer side and rise up against the bottom near the inner side. At spiral troughs with the diameter more than 1 m near the outer side there is secondary transverse circulation with different direction of the water currents. Between the first and secondary circulations there exists a transition zone without any circulation.
Conclusion. *The mechanism of particles separation by density at a spiral separator has been discovered. The basic motive powers of particles stratification in a flow are lift forces which occur because of capillary and gravitational waves motion and flow transverse circulation.*

Key words: *spiral separation; stratification mechanism; capillary and gravitational waves; flows transverse circulation.*

Research aim is to investigate the mechanism of mass transfer at spiral separators and to determine motive powers of particles stratification in a flow.

The current state of the theory and practice of spiral separation is sufficiently explored [1–5]. Mass transfer and separation of particles by density is largely determined by water flows features. The water flows at spiral devices refer to complex modes of fluid motion. They have no fixed depth and speed along the width of the trough. Within one trough, the water flow has several modes and states simultaneously, from laminar to turbulent supercritical.

The state and modes of the water flows are determined by the Froude number:

$$\mathrm{Fr} = \frac{v^2}{gH}, \tag{1}$$

and by the Reynolds number:

$$\mathrm{Re} = \frac{v \cdot H}{\nu}, \qquad (2)$$

where v is the speed of the water flow, m/s; H is the depth of the water flow, m; g is the gravitational acceleration, m/s^2; ν is the kinematic viscosity coefficient, m^2/s [6].

Experimental determination of the Froude number and the Reynolds number for the water flows in straight and spiral troughs and the obtained data comparison by the graph Fr = *f*(Re) shows that the values of laminar, transition, and turbulent modes almost coincide [7]. The major part of a flow at a spiral trough is characterized by Fr number of more than one, which indicates “rough” state of a flow, where free surface is distinguished by the presence of waves. An only the minor part of the water flow near the spiral trough inner side has “smooth” state without waves under Fr < 1. The state of the flow under Fr = 1 should be referred to critical.

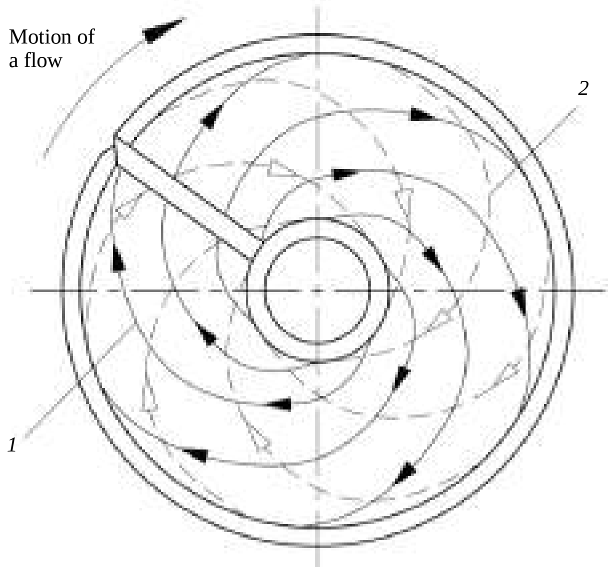

Fig. 1. The scheme of water circulation:
1 – motion of the surface water currents; *2* – motion of the water current at the bottom

Рис. 1. Схема циркуляции воды:
1 – движение поверхностных струй воды; *2* – движение донных струй воды

The water flows at spiral devices refer to complex modes of fluid motion. They have no fixed depth and speed along the width of the trough. Within one trough, the water flow has several modes and states simultaneously, from laminar “smooth” (Re < 300; Fr < 1) and laminar “rough” (Re < 300; Fr > 1) to turbulent “rough” (Re > 3400; Fr > 1).

Waves at a spiral trough with a smooth profile have a form resembling coastal waves with a prominent wave crest in front. At a spiral trough with a complex profile, waves have a complex pattern. Depending on the water flow parameters and the correlation of surface tension force and gravitational force there occur whether capillary, or gravitational, or both waves together.

Capillary waves occur in spiral water flows with the number of Reynolds up to ~ 3000 and with the number of Froude of more than one. They are observed at all spiral troughs in the flow bordered to the inner side.

Capillary waves lack fixed depth neither along the radius, nor along the spiral line. The depth of a wave grows from the axis to the outer side and reduces from the wave’s crest to the back side. Capillary wave parameters (speed, depth, length, and frequency) in a spiral flow have stable character and remain practically unchanged if the water flow and pulp density in the power supply is varied.

Gravitational waves occur at the number of Reynolds higher than ~ 3000 and the number of Froude higher than one, and exist at spiral troughs near the outer side.

Variation and complexity of water flows wave motion at the narrowing trough should lead to circulating flows generation. The hypothesis on the presence of water circulation at a spiral trough was made as early as 1945 [8].

Results. Investigations on the determination of circulation at spiral troughs have shown that the upper flows move along the unfolding spirals gradually approaching the outer side. Getting close to the bottom, the water currents move along the folding spirals with a decreasing radius. At that, water masses, on the one hand, circle around the axis of a spiral trough, on the other hand, around the spiral axis of a flow. This motion of water masses is conditioned on the difference between the centrifugal forces in depth.

The character of the water flows motion at the spiral trough is schematically represented at fig. 1.

The presence of transverse circulation has been experimentally determined, the scheme of which is represented at fig. 2, *a*. When spiraling down along the trough, the water currents sink to the depth of a flow near the outer side and rise up against the bottom near the inner side. Transverse circulation at a spiral trough is a stable notion; it hasn't been disturbed even in the trough with riffles at the working surface along the spiral lines.

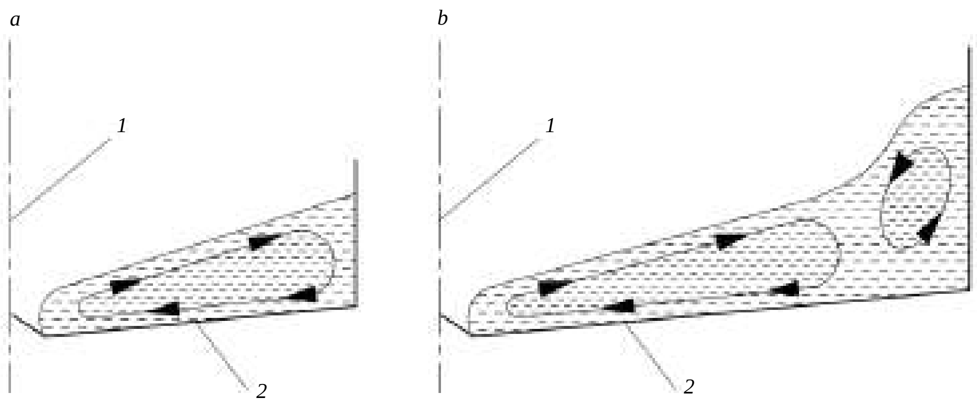

Fig. 2. The scheme of the water flows' transverse circulation:
a – the scheme of transverse circulation; *b* – secondary transverse circulation; *1* – spiral trough axis; *2* – spiral trough
Рис. 2. Схема поперечной циркуляции водных потоков:
а – схема поперечной циркуляции; *b* – двойная поперечная циркуляция; *1* – ось винтового желоба; *2* – винтовой желоб

When investigating at spiral troughs with the diameter more than 1 m near the outer side, secondary circulation with different direction of the water currents has been discovered (fig. 2, *b*) [7].

Secondary transverse circulation occurs practically at once at the first coil and is observed down along the trough near the outer side up to the unloading part. Between the first and secondary circulations there exists a transition zone without any circulation.

In general, the presence of transverse circulation should play a significant role in mineral particles lower layers motion towards the axis of the device and in the solid phase disintegration in a flow.

Mass transfer at a spiral trough significantly differs from water mass transfer. This difference has been experimentally observed at the spiral trough with the diameter

0.5 m and coils pitch 0.35 m, and elliptic cross section. The obtained experimental data after mathematical treatment are represented at fig. 3.

The analysis of dependences represented at fig. 3 shows that the introduction of a mass of mineral particles into the spiral water flow leads to the switch of the flow's separate sections laminar mode into the transition mode, and further into the turbulent one. The numbers Fr and Re are higher at pulp motion, than at water motion. Depth and speed of a flow at its major part which is closer to the trough's axis is higher at pulp motion, than at water motion.

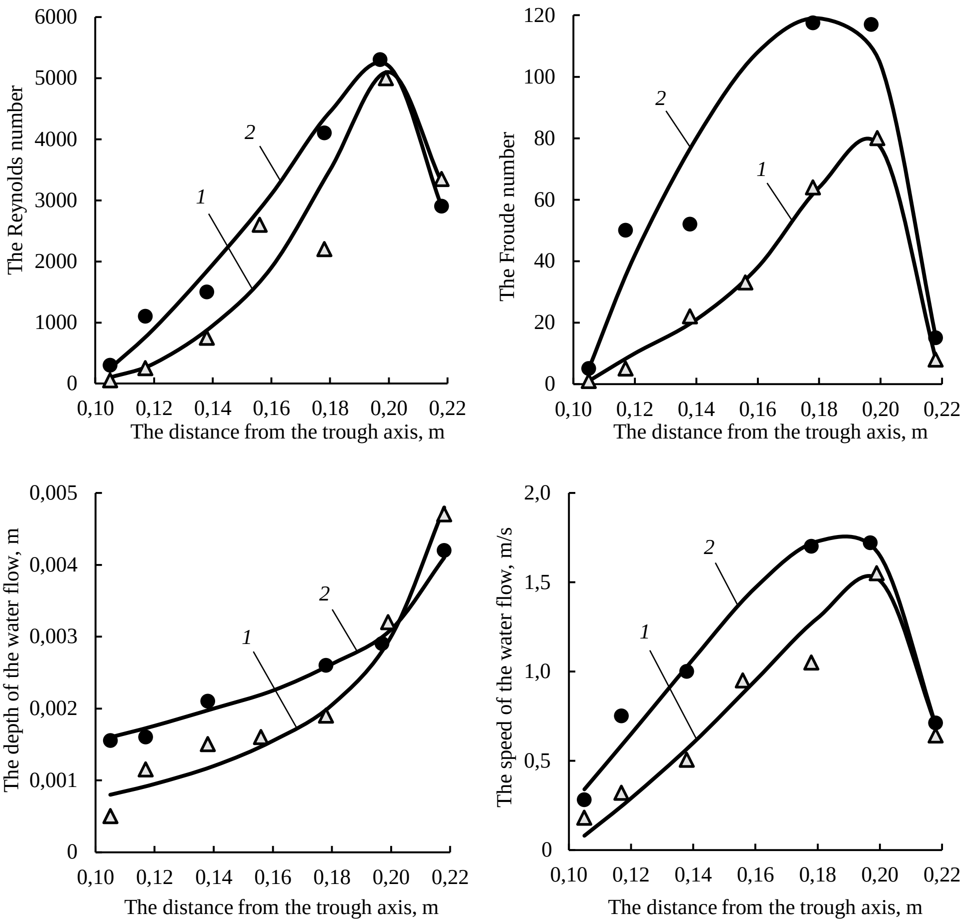

Fig. 3. The parameters of a water flow – *1* and the pulp flow with the mass share of solid in the power supply 31 % – *2* at a spiral trough

Рис. 3. Параметры водного потока – *1* и потока пульпы с массовой долей твердого в питании 31 % – *2* на винтовом желобе

Mass share of solid in a pulp flow at a spiral trough is not identical across the width. It is higher near the inner side reaching 60–66% of solid, and it is lower near the trough's periphery where only water and slime move. As experiments of L. G. Podkosov and others have shown [9], mass share of solid in pulp near the inner side depends on the track length. Thus, at trough's length of 1.75 of a coil, mass share of solid in pulp is 62.0%, and at length of 2.75 of a coil – 65.2%, at length of 6 coils – 66.4%.

Spiral separators and sluices are meant for mineral particles separation by density in the flow of water moving along the inclined plane. Apart from separating the particles by density, stratification of particles by size inevitably occurs. The mechanism of particles stratification by size and density at spiral separators is carried out in the following manner.

Under the action of the inner currents, mineral particles form into longitudinal bands which are the elements of the transfer of solid in the water flow. At a definite water flow mode, particles motion is carried out with the help of the capillary waves in the form of separate portions. At a spiral trough with a smooth profile, the water flows replete with mineral particles, transport particles towards the outer side.

The motive powers of particles stratification in a flow are lift forces [7]. Lift forces result from capillary waves motion because surface flows possess higher speeds than undercurrents. Within the limits of such wave transverse circulation occurs which predetermines vertical velocity component. Their values are of the same order as the lift forces from undercurrents.

Particles disintegration in a pulp flow is undoubtedly also determined by their encounter which occurs because of velocity gradient in depth. Being in the disintegrated state, particles in a spiral flow clash, and distance between them increases and decreases.

There inevitably occurs "sifting" of the minor heavier particles into the spans between the coarse particles. At that lighter coarse particles move in the upper layers of a flow by means of their "wedging up" and displacement by the minor particles [10]. This natural process of particles stratification by size and density is called *segregation*.

The processes of segregation are widely known at solid particles transportation by water both in natural conditions and at concentrating gravitational devices. The presence of additional impacts on a pulp flow, such as centrifugal force (for a spiral separator) or inertial vibrational forces (for a concentrating table, a jigging machine, and a hydraulic screen) intensifies material segregational stratification by size and density [10–16].

Particles stratification by size and density goes on simultaneously. Stratification by density can be intensified with the help of oscillations and upward water flow, and the higher total mobility and disintegration of particles is, the better stratification by density and the worse stratification by size is.

Stratification by density occurs when a heavy particle can advance into the lower layer if under the particle an intergranular channel of a slightly bigger size forms. In the process of a heavy particle motion through the layer of fine light particles it has to overcome resistance of the surrounding particles [7].

Transverse circulation significantly influences the process of particles stratification by density. Solid phase located within the limits of the lower branch of transverse circulation, mowing downwards gradually shifts towards the axis of the device under the effect of hydrodynamic pressure which is the result of gravitational force, centrifugal force, and friction force. This shift doesn't depend on the presence of the heavy particles in this layer. The whole layer shifts. Heavy particles surrounded by the particles of a waste rock comply with the general character of the whole layer of the particles motion. At that, heavy particles gradually advance into the field of a flow with the shallower depths. Because of this, light particles of the layer under consideration are found within the limits of the transverse circulation upper branch, where the motion is directed along the unfolding spiral towards the outer side. At that, the upper layers of light particles pull away from the axis of a spiral trough.

In the process of the lower layer displacement towards the field of a concentrate, there occurs the displacement of lighter particles by the heavier particle into the upper layers. By means of this, heavy particles concentration near the inner side increases.

The velocity of the pulp transverse flow at a spiral trough is directly proportional to the velocity of the pulp longitudinal flow. The larger the flow's depth is, together with the relation of coils pitch to the trough's diameter and the angle of transverse section to the horizon, the higher the transverse circulation velocity is.

Thus, when concentrating at a spiral device, heavier particles center near the inner side of the trough side, when the lighter particles center near the outer side, which makes it possible to divide them as the pulp comes down the trough.

Results area of application. The process of stratification by density at a spiral device is more effective for a narrow grain size class of the primary product. If heavy minerals are generally represented by “slime” particles, then for their isolation into a heavy product mainly laminar mode of pulp motion along the spiral trough is required. Therefore, in order to eliminate the effect of size on the separation results, spiral devices are divided into spiral separators and spiral sluices which are distinguished by the profile of the trough transverse section. The former are applied for the concentration of the particles with the size of 0.071–2 mm, the latter are applied for the concentration of the particles with the size of 0.03–0.5 mm.

Conclusion. The basic feature of mass transfer at spiral devices is the presence of capillary and gravitational waves, generation of circulating flows moving in the upper layers along the unfolding spirals and along the folding spirals at the bottom. Motive powers of particles stratification in a flow are lift forces and transverse circulations of flows.

REFERENCES

1. Auret L., Haasbroek A., Holtzhausen P., Lindner B. Online concentrate band position detection for a spiral concentrator using a Raspberry Pi. XXVII Int. Min. Proc. Cong., 2014. Stellenbosch University, South Africa, pp. 83–92.

2. Konovalov A. B., Aleksandrova T. N., Korchevenkov S. A. [Developing the methodology of determining the characteristics of water flowing along the trough of a spiral separator with the account of its geomechanical characteristics]. *Gornyi informatsionno-analiticheskii biulleten' (nauchno-tekhnicheskii zhurnal) – Mining Informational and Analytical Bulletin (scientific and technical journal)*, 2014, no. S4-6, pp. 26–32. (In Russ.)

3. Prabal Kumar Agrwal, Sanket Bacchuwar, G. V. Rao, and S. K. Sharma. Optimisation of process parameters of spiral concentrator for beneficiation of iron ore stacked slimes from Kirandul, Chattisgarh, India. Proc. XXVIII Int. Min. Proc. Cong., 2016. 10 p.

4. Darryel Boucher, Joshua Sovechles, Zhoutong Deng, Raymond Langlois, Thomas W. Leadbeater, and Kristian E. Waters. Observation of wash water effect on particle motion in a spiral concentrator by positron emission particle tracking. Proc. XXVIII Int. Min. Proc. Cong., 2016. 12 p.

5. Maryam Sadeghi, Claude Bazin, Pier-Olivier Devin, François Lavoie, Daniel Hodouin, Mariléne Renaud. Control of spiral concentrators for the concentration of iron ore. Proc. XXVIII Int. Min. Proc. Cong., 2016. 12 p.

6. Vinnikov V. A., Karkashadze G. G. *Gidromekhanika: uchebnik dlia vuzov* [School book for the institutions of higher education “Hydromechanics”]. Moscow, MSMU Publ., 2003. 302 p.

7. Ivanov V. D., Prokop'ev S. A. *Vintovye apparaty dlia obogashcheniia rud i peskov v Rossii* [Spiral devices for ore and sand concentration in Russia]. Moscow, Daksi Publ., 2000. 239 p.

8. Gleeson W. Why the humphreys spiral works. *Engineering and Mining Journal*, 1945, March, pp. 85–86.

9. Podkosov L. G., Brodkina E. P., Komissarov O. S. [Investigating the conditions of materials stratification in a spiral separator]. *Trudy Vserossiiskogo nauchno-issledovatel'skogo instituta mineral'nogo syr'ia – Proceedings of N. M. Fedorovsky All-Russian Research Institute of Mineral Raw Materials*, Moscow, Nedra Publ., 1970, pp. 142–148. (In Russ.)

10. Bochkovskii V. M. [Stratification as a primarily important branch of gravitation theory and practice]. *Gornyi zhurnal – Mining Journal*, 1954, no. 1, pp. 47–55. (In Russ.)

11. Morozov Yu. P. [Analysis of the gravity separation of minerals in the constrained conditions of motion]. *Izvestiya vysshikh uchebnykh zavedenii. Gornyi zhurnal – News of the Higher Institutions. Mining Journal*, 2011, no. 4, pp. 93–98. (In Russ.)

12. Shokhin V. N., Lopatin A. G. *Gravitatsionnye metody obogashcheniia: uchebnik* [School book “Gravitational Methods of Concentration”]. Moscow, Nedra Publ., 1980. 400 p.

13. Blekhman I. I., Dzhanelidze G. Iu. *Vibratsionnoe peremeshchenie* [Vibrational displacement]. Moscow, Nauka Publ., 1964. 410 p.

14. Ivanov V. D. [Stratification of mineral particles by density, size, and shape in water flows along the inclined surface]. *Izvestiya vuzov. Tsvetnaya metallurgiya – Universities' Proceedings. Nonferrous Metallurgy*, 1985, no. 1, pp. 3–7. (In Russ.)

15. Ivanov V. D. [On the mechanics of mineral particles stratification at spiral devices]. *Izvestiya vuzov. Tsvetnaya metallurgiya – Universities' Proceedings. Nonferrous Metallurgy*, 1986, no. 2, pp. 11–15. (In Russ.)

16. Pelevin A. E. [Probability of bolting particles through the mesh and the process of segregation on a bolting machine]. *Izvestiya vysshikh uchebnykh zavedenii. Gornyi zhurnal – News of the Higher Institutions. Mining Journal*, 2011, no. 1, pp. 119–129. (In Russ.)

Received 15th May, 2018

Prokop'ev S. A., Pelevin A. E., Morozov Iu. P. Some features of mass transfer at spiral devices. Izvestiya vysshikh uchebnykh zavedenii. Gornyi zhurnal. 2018. No. 7. Pp. 67–74.

Information about authors

Prokop'ev Sergei Amperovich – Chairman of OOO Manufacturing Company Spirit. E-mail: s.a.prok@gmail.com
Pelevin Aleksei Evgen'evich – Doctor of Engineering Sciences, Associate professor, professor of the Department of Minerals Processing of the Ural State Mining University. E-mail: a-pelevin@yandex.ru
Morozov Iurii Petrovich – Doctor of Engineering Science, Professor, professor of the Department of Minerals Processing of the Ural State Mining University. E-mail: tails2002@inbox.ru

ОСОБЕННОСТИ МАССОПЕРЕНОСА НА ВИНТОВЫХ АППАРАТАХ

Прокопьев С. А.[1], Пелевин А. Е.[2], Морозов Ю. П.[2]
[1] ООО ПК «Спирит», Иркутск, Россия.
[2] Уральский государственный горный университет, Екатеринбург, Россия.

Целью работы *является рассмотрение механизма массопереноса на винтовых сепараторах и определение движущих сил расслоения частиц в потоке.*
Методика проведения исследований. *Рассмотрены вопросы массопереноса водных потоков и пульпы на винтовых сепараторах. Для оценки состояния и режимов потоков определены числа Фруда и Рейнольдса. Показано, что водные потоки на винтовых аппаратах относятся к сложным формам движения жидкости. Они не имеют постоянной глубины и скорости по ширине желоба. В одном желобе водный поток одновременно имеет несколько режимов и состояний – от ламинарного «спокойного», ламинарного «бурного» до турбулентного «бурного».*
Результаты и их анализ. *Установлено наличие капиллярных и гравитационных волн, поперечных циркуляций потоков. Исследования по определению циркуляций на винтовых желобах показали, что верхние потоки движутся по развертывающимся спиралям, постепенно приближаясь к внешнему борту. Оказавшись вблизи дна, водные струи движутся по свертывающимся спиралям с уменьшающимся радиусом. Экспериментально определено наличие поперечной циркуляции потока. Водные струи при движении вниз по желобу опускаются в глубь потока у внешнего борта и поднимаются вверх относительно дна у внутреннего борта. На винтовых желобах диаметром более 1 м у внешнего борта присутствует вторичная поперечная циркуляция с другим направлением водных струй. Между первой и вторичной циркуляциями существует промежуточная зона без циркуляции.*
Вывод. *Раскрыт механизм разделения частиц по плотности на винтовом сепараторе. Основными движущими силами расслоения частиц в потоке являются подъемные силы, которые возникают от движения капиллярных и гравитационных волн и поперечной циркуляции потока.*

Ключевые слова: *винтовая сепарация; механизм расслоения; капиллярные и гравитационные волны; поперечная циркуляция потоков.*

DOI: 10.21440/0536-1028-2018-7-67-74

БИБЛИОГРАФИЧЕСКИЙ СПИСОК

1. Auret L., Haasbroek A., Holtzhausen P., Lindner B. Online concentrate band position detection for a spiral concentrator using a Raspberry Pi. XXVII International Mineral Processing Congress, 2014. Stellenbosch University, South Africa. P. 83–92.
2. Коновалов А. Б., Александрова Т. Н., Корчевенков С. А. Разработка методики определения характеристик потока воды, текущей по желобу винтового сепаратора, с учетом его геомеханических характеристик // ГИАБ. 2014. № S4-6. С. 26–32.
3. Prabal Kumar Agrwal, Sanket Bacchuwar, G. V. Rao, and S. K. Sharma. Optimisation of process parameters of spiral concentrator for beneficiation of iron ore stacked slimes from Kirandul, Chattisgarh, India. Proc. XXVIII International Mineral Processing Congress, 2016. 10 p.
4. Darryel Boucher, Joshua Sovechles, Zhoutong Deng, Raymond Langlois, Thomas W. Leadbeater, and Kristian E. Waters. Observation of wash water effect on particle motion in a spiral concentrator by positron emission particle tracking. Proc. XXVIII International Mineral Processing Congress, 2016. 12 p.
5. Maryam Sadeghi, Claude Bazin, Pier-Olivier Devin, François Lavoie, Daniel Hodouin1, Marilène Renaud. Control of spiral concentrators for the concentration of iron ore. Proc. XXVIII International Mineral Processing Congress, 2016. 12 p.
6. Винников В. А., Каркашадзе Г. Г. Гидромеханика: учебник для вузов. М.: МГГУ, 2003. 302 с.
7. Иванов В. Д., Прокопьев С. А. Винтовые аппараты для обогащения руд и песков в России. М.: Дакси, 2000. 239 с.
8. Gleeson W. Why the humphreys spiral works // Engineering and Mining Journal. 1945. March. P. 85–86.

9. Подкосов Л. Г., Бродкина Е. П., Комиссаров О. С. Исследование условий разделения материала в винтовом сепараторе // Труды ВИМСа. М.: Недра, 1970. С. 142–148.
10. Бочковский В. М. Расслаивание как наиболее важный раздел теории и практики гравитации // Горный журнал. 1954. № 1. С. 47–55.
11. Морозов Ю. П. Анализ гравитационного разделения минералов в стесненных условиях движения // Известия вузов. Горный журнал. 2011. № 4. С. 93–98.
12. Шохин В. Н., Лопатин А. Г. Гравитационные методы обогащения: учебник. М.: Недра, 1980. 400 с.
13. Блехман И. И., Джанелидзе Г. Ю. Вибрационное перемещение. М.: Наука, 1964. 410 с.
14. Иванов В. Д. Расслоение минеральных частиц по плотности, крупности и форме в водных потоках по наклонной плоскости // Известия вузов. Цветная металлургия. 1985. № 1. С. 3–7.
15. Иванов В. Д. О механизме расслоения минеральных частиц на винтовых аппаратах // Известия вузов. Цветная металлургия. 1986. № 2. С. 11–15.
16. Пелевин А. Е. Вероятность прохождения частиц через сито и процесс сегрегации на вибрационном грохоте // Известия вузов. Горный журнал. 2011. № 1. С. 119–129.

Сведения об авторах:

Прокопьев Сергей Амперович – председатель совета директоров ООО ПК «Спирит». E-mail: s.a.prok@gmail.com
Пелевин Алексей Евгеньевич – доктор технических наук, доцент, профессор кафедры обогащения полезных ископаемых Уральского государственного горного университета.
E-mail: a-pelevin@yandex.ru
Морозов Юрий Петрович – доктор технических наук, профессор, профессор кафедры обогащения полезных ископаемых Уральского государственного горного университета. E-mail: tails2002@inbox.ru