The relevance of flotation classification in a closed grinding cycle

T I Intogarova¹, O S Valieva¹ and Y P Morozov²

¹ Mirny Polytechnic Institute (Branch), Ammosov North-Eastern Federal University, 14, Oyunsky ave., Mirny, 678170, Russia
² Ural State Mining University, 30, Kuibyshev ave., Yekaterinburg, 620144, Russia

E-mail: tatyana.intogarova@mail.ru

Abstract. The article discusses a brief history of development of the flotation classification, reflects current trends in the development of flotation ore dressing, in foreign and domestic enrichment practice. Variants of implementation of the flotation classification, due to behavioral patterns, the degree of interaction are discussed. The relationship of flotation and gravitational processes in the flotation classification was identified and confirmed by theoretical and experimental studies. The directions of application of the flotation classification in a closed grinding cycle were considered. Variants of practical application of the flotation classification in a closed grinding cycle for sulfide ores and on tailings for various products of the grinding cycle, in the modes of froth flotation and separation were analyzed, the main advantages were identified. Ways to achieve optimal conditions for flotation classification were described. A new direction for the flotation classification using tapering chutes was identified. It is possible to obtain a conditional concentrate of flotation classification in a closed grinding cycle with the enrichment of the froth product in the tapering chutes. The flotation classification of tailings ensures the maximum extraction of flotation minerals into the froth with the tailings flotation classification being drained. A schematic diagram of flotation classification enrichment in a closed grinding cycle is presented, and the results of calculating final flotation classification parameters for sulphide copper ore dressing are presented. Flotation classifiers in a closed grinding cycle reduce energy costs and increase technological indicators of the enrichment of mineral and industrial raw materials.

1. Practical Application of the Fleet Classification Process

Combining the flotation process with other enrichment processes is a promising direction for improving the technology of enrichment of minerals. The method of flotation classification was developed: flotation and hydraulic classification are combined. The processes of flotation gravity are based on the simultaneous use of differences in density, particle size and their ability to be fixed at the interface between the liquid and gas phases [1].

In the 1960s, N.F. Meshcheryakov proposed a method for flotation classification, according to which operations of flotation and hydraulic classification are combined [2]. The flotation classification process is implemented in a spiral classifier. Since 1962, flotation classification has developed by creating machines, their improvement and testing. The first flotation classifiers were developed from mechanical classifiers. In 1964, Yu.S. Badeev developed a prototype of a flotation classifier, tested it in industrial conditions in the treatment of monometallic lead ore [3].
Modern trends in the development of ore flotation concentration include the use of high-performance column and vat flotation machines and implementation of flotation into a closed grinding cycle in order to extract exposed particles of valuable components. The advantages of these flotation machines are high productivity, low capital and operating costs and a small footprint. The scope of these types of flotation machines is constantly expanding [4-10].

At plants which process sulphide ores, it is recommended to separate copper “heads” to reduce the sludge of valuable minerals. 50-55% of the total copper extraction with a mass fraction of copper of 25-26% are extracted into the resulting concentrate of copper “heads” [11, 12].

The Outotec SkimAir unit, which operates as a flotation cell and classifier in a closed grinding cycle, has become widespread in foreign practice of mineral processing [13]. The plant processes half or two thirds of sands of the hydrocyclones, the rest of sands return to the mill. The particle size of SkimAir feed reaches 10 mm, the solids content is up to 65%. High-speed flotation is widely used in the benrichment of gold-bearing [14] and nickel [15] ores. At the Canadian copper, zinc and gold plant, SkimAir flotation machines have increased gold recovery by 5%. At the Australian gold mine, copper and gold recoveries increased by 2.5% after the installation of the SkimAir cell [16].

There are examples of the use of SkimAir flotation machines at Russian plants during gold processing at the Omsukchan plant. There was a deterioration in quality of raw materials. This machine made it possible to increase the extraction of gold by 2%, and silver - by 1% [17].

2. Applications of the flotation classification process in a closed grinding cycle

To create new solutions in the field of sulfide ore dressing, the employees of the North-Eastern Federal University and the Ural State Mining University are studying regularities of the flotation classification process and development of new designs for flotation classifiers [18, 19].

Combining the processes of flotation and hydraulic classification in the flotation classifier leads to their interaction. Pulp aeration helps to increase the rates of ascending flows in the flotation classifier by reducing the cross-sectional area of the pulp by air bubbles. In this case, gravitational separation is carried out in more constrained conditions. Theoretical and experimental studies prove that an increase in aeration in the upward flow of hydraulic classification in a flotation classifier increases the size of separation and improves the efficiency of hydraulic classification [20]. The efficiency of classification, calculated according to the Hancock-Luken criterion, reaches 60-65% in industrial flotation classifiers, and 80-85% - in laboratory ones.

Studies on the reduction of removal of fine particles into sands in fleet classifiers with various sand unloading devices have established that it is necessary to form a bed at the bottom of the fleet classifier to obtain the best indicators of hydraulic classification. In this case, the mass fraction of solids should be more than 55-60% [21].

The advantages of flotation classifiers include the ability to install flotation classifiers on different products in the grinding cycle. Unlike SkimAir flotation machines, flotation classifiers can work on sands of hydrocyclones, the discharge of the classifier or the unloading of the mill.

The scheme with the flotation classification of sands of the hydraulic classification makes it possible to extract the minerals from sands into the concentrate as they are opened and thereby avoid overgrinding of these particles. The scheme with flotation classification of the hydraulic classification discharge ensures the circulation of sands, which makes it possible to accept smaller standard sizes of the flotation classifiers. When processing ores, such a scheme allows obtaining a conditioned concentrate in the froth product of the flotation classifier, a discharge that is sent to the flotation operation according to the existing scheme, and sands returned to the mill.

Flotation classification with a closed grinding cycle in was included in the technological scheme at the Sibay concentration plant. The flotation classifier was installed at the discharge of hydrocyclones, sands were obtained, returned for regrinding, the discharge was sent to flotation, and the foam product was sent to the finished copper concentrate. The flotation classifier was tested on copper-zinc ores of the Sibay deposit and copper ores of the Gay and Sibay deposits. The technological indicators of tests showed the possibility of obtaining a conditioned copper concentrate during the enrichment of these
deposits. The flotation classification process was tested at the Krasnouralsk concentrator in the grinding department of the third section. The test results showed an increase in the recovery of copper, gold and silver.

Flotation classification in a closed grinding cycle can be implemented without hydraulic classification as a classifying device, but such schemes are advisable to use when processing tailings. In industrial conditions, this option was tested at the Buribay concentrator, which increased the technological indicators.

In the flotation classifiers, it is possible to implement various methods of flotation concentration, which is achieved by supplying the initial feed to different levels of the flotation classifier. The implementation of froth flotation is achieved by supplying the initial feed to the inside of the chamber, while the foam separation is achieved by supplying feed to the froth layer or directly to the foam.

The advantages of froth separation over flotation are obvious: low energy costs and short process duration, high separation efficiency of coarse-grained material, highly diluted and dense slurries. Flotation classifiers have been tested both in laboratory and industrial conditions under various modes. It has been established that the foam separation mode is more preferable, since when the flotation classifier operates in a closed grinding cycle, the size of the material fed into it can reach 10 mm.

An important advantage of the flotation classifiers is the ability to regulate the technological parameters of the process in a wide range, which ensures optimal conditions for the separation of various types of feedstock. Optimal conditions for flotation classification are achieved by the air flow rate supplied to the aeration system; current strength during the implementation of the electrified flotation classification mode; the output of the top product of the tapering flotation classifier; mass fraction of a solid flotation classifier in sands.

A fundamentally new direction of flotation classification is the use of tapered chutes for enrichment of the foam product. These variants make it possible to obtain one conditioned or several different quality foam products, reduce energy and operating costs while increasing the enrichment indicators. The enrichment of the foam product in the tapering troughs provides for the formation of different-quality foam layers and foam division into enrichment products [22]. The formation of different-quality foam layers is due to the secondary concentration of minerals, which has been studied in [23]. Narrowing the foam flow due to an increase in the foam layer height and a decrease in the surface area of the foam reduces the coalescence of bubbles, and increases the likelihood of re-fixing of the released floating particles in the foam. Increasing the thickness of the foam layer facilitates the separation of the foam stream into different-quality top and bottom products.

The use of tapering chutes at Krasnouralsk, Sibay, Buribay enrichment plants provided a high quality concentrate in the top product, comparable to the concentrate after one or several cleaning operations of flotation [24]. The taper chute bottom product is enriched by the conventional flotation scheme. The tapering chutes provide for the regulation of the output of the overhead product by means of a gate, which is lowered or raised, thereby providing a predetermined amount of overhead product.

In China, in the laboratory of Hebei United University, research has been carried out to study the flotation classification of iron hematite ore, the design of the flotation classifier provides for the separation of the foam product in a tapering chute. The positive results made it possible to install a flotation classifier in the tailings processing shop in a closed grinding cycle. The mass fraction of iron in the initial feed of the fleet classifier was about 20%. The flotation classifier implements the reverse flotation process. As a result of optimization of the operating parameters of the machine in the upper product of the tapering chute, tailings with a mass fraction of iron of less than 12% were obtained.

Designs of flotation classifiers with tapering troughs are protected by RF patents for inventions No. 2548866, No. 2608120, No. 2690078.

However, from all options considered, it is advisable to use the flotation classification in a closed grinding cycle at the discharge of a hydrocyclone. It is proposed to enrich the foam product in tapering troughs. The schematic diagram of flotation classification in a closed grinding cycle is shown in Figure 1. The initial feed goes to grinding, the ground product goes to the hydraulic classification, where it is separated into a drain and sands. The discharge of the hydrocyclone is sent to the flotation classification as a classifying device, but such schemes are advisable to use when processing tailings. In industrial conditions, this option was tested at the Buribay concentrator, which increased the technological indicators. In the flotation classifiers, it is possible to implement various methods of flotation concentration, which is achieved by supplying the initial feed to different levels of the flotation classifier. The implementation of froth flotation is achieved by supplying the initial feed to the inside of the chamber, while the foam separation is achieved by supplying feed to the froth layer or directly to the foam. The advantages of froth separation over flotation are obvious: low energy costs and short process duration, high separation efficiency of coarse-grained material, highly diluted and dense slurries. Flotation classifiers have been tested both in laboratory and industrial conditions under various modes. It has been established that the foam separation mode is more preferable, since when the flotation classifier operates in a closed grinding cycle, the size of the material fed into it can reach 10 mm. An important advantage of the flotation classifiers is the ability to regulate the technological parameters of the process in a wide range, which ensures optimal conditions for the separation of various types of feedstock. Optimal conditions for flotation classification are achieved by the air flow rate supplied to the aeration system; current strength during the implementation of the electrified flotation classification mode; the output of the top product of the tapering flotation classifier; mass fraction of a solid flotation classifier in sands. A fundamentally new direction of flotation classification is the use of tapered chutes for enrichment of the foam product. These variants make it possible to obtain one conditioned or several different quality foam products, reduce energy and operating costs while increasing the enrichment indicators. The enrichment of the foam product in the tapering troughs provides for the formation of different-quality foam layers and foam division into enrichment products [22]. The formation of different-quality foam layers is due to the secondary concentration of minerals, which has been studied in [23]. Narrowing the foam flow due to an increase in the foam layer height and a decrease in the surface area of the foam reduces the coalescence of bubbles, and increases the likelihood of re-fixing of the released floating particles in the foam. Increasing the thickness of the foam layer facilitates the separation of the foam stream into different-quality top and bottom products. The use of tapering chutes at Krasnouralsk, Sibay, Buribay enrichment plants provided a high quality concentrate in the top product, comparable to the concentrate after one or several cleaning operations of flotation [24]. The taper chute bottom product is enriched by the conventional flotation scheme. The tapering chutes provide for the regulation of the output of the overhead product by means of a gate, which is lowered or raised, thereby providing a predetermined amount of overhead product. 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classification, the process takes place in a vat-type apparatus with tapering troughs. The foam product enriched in tapering troughs, the drain and sands combined with sands of the hydrocyclone and returned to regrinding are outputs of the flotation classification.

![Diagram of flotation classification](image)

**Figure 1.** The schematic diagram of flotation classification in a closed grinding cycle

The above scheme ensures the circulation of sands past the flotation classifier, which allows us to accept smaller standard sizes of the flotation classifiers. This scheme makes it possible to increase the indicators of further flotation due to the fact that the exposed particles of valuable minerals are extracted in the flotation classifier immediately as they are opened during the grinding process.

### 3. Flotation classification in a closed grinding cycle with enrichment of the foam product in tapering chutes

Using a large amount of accumulated data on the flotation classification in a closed grinding cycle, a method for modeling the flotation classification in a closed grinding cycle with waste tailings in the drain has been developed.

The modeling was carried out for the copper ore processing conditions of the Yelenov deposit using the method of decomposition modeling. The chambers of flotation machines typical elements of the scheme. When decomposing the circuit, two-parameter coding of the circuit topology is used. Connections of typical elements with each other are specified by a two-dimensional array in the form of an NxN matrix, where N is the number of typical elements in the circuit.

Based on the experimental data of the qualitative-quantitative scheme of flotation classification in a closed grinding cycle (Figure 2), the bottom product of the tapering chute enters the flotation section with a yield of 33.39%, the mass fraction of copper is 13.22% and the extraction of copper is 50.60%.

When simulating the flotation scheme, the main flotation operation is excluded from the simulation. The scheme for modeling the process of flotation classification with flotation is shown in Figure 3. The scheme includes cleaning flotation operations I and II. The number of chambers for the cleaning flotation operations I is 6, for the cleaning flotation operations II is 2. The simulation results are presented in Table 1.
Figure 2. The qualitative-quantitative scheme of flotation classification in a closed grinding cycle.

Table 1 - Balance for the final products of the flotation classification scheme with flotation producing waste tailings

| Name of the product                        | Output, % | Mass share, % | Extraction, % |
|-------------------------------------------|-----------|---------------|---------------|
| Flotation Classifier Concentrate          | 5,17      | 20,00         | 44,20         |
| Flotation concentrate                     | 5,17      | 20,50         | 45,30         |
| **Total**                                 | **10,34** | **20,30**     | **89,5**      |
| Draining of the fleet classifier          | 60,84     | 0,20          | 5,20          |
| Flotation tailings                        | 28,82     | 0,43          | 5,30          |
| **Total**                                 | **89,66** | **0,27**      | **10,5**      |
| Nutrition                                 | 100       | 2,34          | 100           |

Figure 3. The scheme of modeling the process of flotation classification with flotation.
The simulation results show that the separation of tailings with a mass fraction of copper of 0.2% in the outlet of the flotation classifier provides an increase in the extraction of copper into conditioned copper concentrate by 7.5%, which indicates the expediency of using the flotation classification in a closed grinding cycle.

4. Conclusion
The following conclusions about the relevance of flotation classification in a closed grinding cycle can be drawn:
- Implementation of flotation classification into the grinding cycle, excluding the operation of hydraulic classification in hydrocyclones from the scheme.
- Possibility of using a flotation classifier for the implementation of froth flotation and froth separation modes, as well as adaptation to any type of feedstock.
- Possibility of separation of coarse-grained materials.
- Possibility of producing a conditioned concentrate in the foam product of flotation classification.
- Possibility of reducing the machine capacity of the subsequent flotation front.
- Possibility of improving technological parameters by reducing over-grinding.
- Possibility of obtaining dump tailings in the discharge of the flotation classifier.

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