Development of a resource-saving technology for industrial processing of hematite-containing raw materials based on computer modelling

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Abstract. The paper presents the results of the research aimed at recovery of hematite from current and stockpiled tailings produced at the mineral processing plant of Olkon JSC. The authors investigated material composition of tailing samples. Using methods of computational fluid dynamics and the ANSYS software, the models of spiral separation of the tailings have been developed. The use of computer modelling has shown that spiral separators can be recommended for tailings processing. The modelling results were confirmed with industrial spiral separation tests conducted at the processing plant. The authors developed a gravity separation technology for processing the magnetic separation tailings and stockpiled tailings. The proposed technology allows recovering hematite concentrate with a hematite iron content of 54.5% and recovery of 75.4% from current tailings containing 5.2% of hematite iron. It was also shown that hematite concentrate can be recovered from stockpiled tailings using the separation technology based on the use of spiral separation. The gravity separation technology provides for resources economy at the mineral processing plant. The use of stockpiled tailing as a raw material source can reduce negative environmental impact.

1. Introduction

Nowadays, the most part of the richest iron ores, which can be easily processed, has been depleted. So, a problem of ore separation with low content of valuable minerals and complex material composition has arisen. The problem requires research and development of technologies and devices, including gravity separation for effective processing of the fine fractions of materials [1].

The mineral processing plant of Olkon JSC, located at the Murmansk region, produces magnetite-hematite concentrate. The processing technology includes several magnetic separation stages to produce magnetite concentrate and two jigging stages to produce hematite concentrate from a non-magnetic fraction of magnetic separation. At present time, the jigging separation does not provide for acceptable content and recovery of hematite to a concentrate in processing hematite ores [2]. Table 1 presents values of yield, content, and recovery of hematite iron in the products of jigging which were obtained during sampling at the processing plant.

| Products | Yield, % | Content of hematite iron, % | Recovery of hematite iron, % |
|----------|----------|-----------------------------|-----------------------------|
| Concentrate | 4.7      | 42.5                        | 37.2                        |
As it can be seen from Table 1, recovery of hematite iron in tailings is about 50%, which means the loss of about half of hematite during jigging. Most part of hematite losses with tailings is particles with diameter less than 0.2 mm, as far as jigging is effective in separating relatively coarse particles [3]. This problem requires development of a new technology for effective separation of fine fractions of tailings.

Also, big losses of hematite with jigging tailings lead to accumulation of significant volumes of this mineral in a tailing dump. This fact allows us to consider a tailing dump as a mining-induced hematite deposit. The amount of the tailing for more than 70 years of the plant’s operation accounts to about 500 million tons [4]. Figure 1 shows satellite images of the tailing dump.

![Satellite images of the tailings dump of Olkon JSC.](image)

Nowadays, one of the new research directions of separation processes is computer modelling based on the Computational Fluid Dynamics (CFD) methods [5]. Computer modelling allows a researcher to investigate hydrodynamics of the water flow and predict separation characteristics such as yield, content, and recovery of valuable mineral [6]. In this study, we applied CFD-modelling to determine the efficiency of using the spiral separators for tailings processing. The aim of this study is to develop a technology for the separation of hematite-containing materials of Olkon JSC using computer modeling, reduce hematite losses with tailings, increase its content and recovery in concentrate, and also save resources at the plant.

2. Methods
A non-magnetic fraction of magnetic separation (current tailings), which is the feed of jigging, was sampled at the mineral processing plant. We analyzed the grain sizes (Figure 2) and mineral and
chemical compositions to set the computer modelling parameters correctly. The mineral analysis has revealed the following mineral composition of the sample: hematite - 10%, magnetite - 1%, quartz and feldspar - 73-75%, amphiboles, mica - 10-12%, other (garnet, epidote, calcite, single grains of sulphides) - 3-4%. The content of total and hematite iron was 9.6% and 7.6%, respectively.

To estimate the possible recovery of hematite from stockpiled tailings, we sampled some of this material from tailings dump. The sample analysis has shown a similar mineral composition of the stockpiled tailing to current tailings and the content of total iron to be about 9.3%, but the content of hematite being lower (3.2%). Grain size characteristics of both samples are also similar with the most part of the material concentrating in -0.6+0.1 mm size class (Figure 2). The analysis of hematite distribution in the both samples shows again that jigging used at the plant for hematite recovery from current tailings does not recover fine hematite fractions and they are accumulated in a tailing dump.

![Figure 2. Granular characteristics, content, and distribution of hematite in samples of current tailings and stockpiled tailings.](image)

We conducted CFD-modelling using the ANSYS software to estimate the efficiency of spiral separation for processing the current tailings. For the modelling objects we selected two spiral concentrators (VSR-500 and SHV-500), both with a diameter of 500 mm. The difference between the separators is the number of turns, distance between turns, and surface profile geometry. VSR-500 has a profile in form of a highly inclined curve and SHV-500 has a profile in form of a lowly inclined curve.

The model development process consists of following stages: creation of 3D geometry of an object, generation of a mesh, setting of simulation parameters and boundary conditions, calculation, analysis of results and adequacy of a model.

The computational meshes consisting of approximately one million tetrahedral cells were generated. The cell size is 8 mm, but in the suspension movement zone, where greater accuracy of calculations is required, the cell size is less than 1 mm.

The ANSYS Fluent software set up the model parameters and boundary conditions. To model the continuous phase movement, we used a Volume Of Fluid (VOF) model [7]; the turbulence of the flow was simulated using a k-ε model [8], and the trajectories of mineral particles were calculated with a Discrete Phase Model (DPM) [9]. The mineral particles flowrate (250 kg/h) and a water flowrate were set as a boundary condition for inlet. Granular and mineral characteristics of the feed were set according to the analyses results presented above.
Confirmation of the simulation results was carried out on the basis of industrial tests of spiral separation. The products obtained during the tests were re-cleaned in laboratory conditions using various gravity methods, high-intensity magnetic separation, and milling. A separation technology based on the results of technological experiments was developed.

3. Results
The advantage of modeling is reducing the time spent on laboratory tests. Calculation of the models designed in ANSYS Fluent allowed us to investigate velocity of suspension, concentration of phases, trajectories of movement, and other results of the simulation which were consistent with studies of others authors [10]. Figure 3 presents mineral particle distribution in a computational domain colored according to their density; hematite particles are colored red. Figure 3 demonstrates the distribution of particles which is typical for spiral separation [11]. The hematite particles have a tendency to concentrate at the inner side of the spiral surface and be recovered in the concentrate. The most part of the particles with intermediate density (colored by light blue) is recovered to the middlings. Quartz and feldspar particles colored blue pass mostly to the tailings and less to the middlings.

![Figure 3. Distribution of mineral particles colored according to density, kg/m³, in models of VSR-500 (A), SHV-500 (B).](image)

While developing a mineral processing technology, it is important to predict the separation indicators such as the yield, the content, and the recovery. The combination of a DPM model and macros developed in C++ allows getting these characteristics (Table 2).

| Products   | Yield, % | Hematite content, % | Hematite recovery, % | Yield, % | Hematite content, % | Hematite recovery, % |
|------------|----------|---------------------|----------------------|----------|---------------------|----------------------|
| VSR-500    |          |                     |                      |          |                     |                      |
| SHV-500    |          |                     |                      |          |                     |                      |
| Concentrate| 6.5      | 78.5                | 51.2                 | 8.7      | 81.9                | 71.5                 |

Table 2. Predicted indicators of spiral separation of current tailings.
The simulation results have shown the advantage of spiral separators against jigging (Table 1) due to more efficient separation of fine fractions of mineral particles. SHV-500 provided for a higher yield, content, and recovery of hematite in a concentrate and VSR-500 provided a richer middling product. The recovery of the valuable mineral in the tailings was 9-16%.

In order to confirm the obtained results, we carried out the industrial tests of spiral separation at the processing plant of Olkon JSC. We used the spiral separator SHV-500 as far as the results of modelling and laboratory experiments showed its higher efficiency. Table 3 presents the results of industrial tests. The usual content of hematite iron in the magnetic separation tailings is less than 10% (tests 4-7). Comparison of industrial tests with results of jigging (Table 1) has shown that spiral separation provides more effective processing of current tailings and decreases losses of fine hematite fractions with tailings. The most part of hematite in spiral separation tailings is hematite particles with diameter less than 0.045 mm which are not processed effectively by gravity separation [12]. This fact explains relatively high recovery of hematite in tailings during test 7 (29.5%). During test 7 content of particle size fraction -0.045 mm in the feed increased to 20%, while during other tests its content was less than 10%.

| Products  | Yield, % | Content of hematite iron, % | Recovery of hematite iron, % |
|-----------|----------|-----------------------------|-----------------------------|
| **Test №1** |          |                             |                             |
| Concentrate | 25.6     | 58.2                        | 80.6                        |
| Middlings | 33.3     | 6.7                         | 12.1                        |
| Tailings  | 41.1     | 3.3                         | 7.3                         |
| Feed      | 100.0    | 18.5                        | 100.0                       |
| **Test №2** |          |                             |                             |
| Concentrate | 34.0     | 56.7                        | 91.0                        |
| Middlings | 37.3     | 3.2                         | 5.6                         |
| Tailings  | 28.7     | 2.5                         | 3.4                         |
| Feed      | 100.0    | 21.2                        | 100.0                       |
| **Test №3** |          |                             |                             |
| Concentrate | 26.5     | 58.2                        | 78.9                        |
| Middlings | 36.2     | 7.5                         | 13.9                        |
| Tailings  | 37.3     | 3.8                         | 7.2                         |
| Feed      | 100.0    | 19.6                        | 100.0                       |
| **Test №4** |          |                             |                             |
| Concentrate | 13.3     | 52.0                        | 85.3                        |
| Middlings | 40.0     | 2.4                         | 11.8                        |
| Tailings  | 46.7     | 0.5                         | 2.9                         |
| Feed      | 100.0    | 8.1                         | 100.0                       |
| **Test №5** |          |                             |                             |
| Concentrate | 8.4      | 31.3                        | 78.9                        |
| Middlings | 51.3     | 0.9                         | 13.8                        |
| Tailings  | 40.3     | 0.6                         | 7.3                         |
| Feed      | 100.0    | 3.3                         | 100.0                       |
| **Test №6** |          |                             |                             |
| Concentrate | 6.1      | 36.1                        | 65.5                        |
| Middlings | 29.6     | 2.4                         | 21.1                        |
Thus, results of industrial tests proved the results of computer modelling and confirmed the feasibility of replacing the jigging machines by the spiral separators.

We conducted further separation of produced products (rough concentrate and middlings) by using two operations of spiral separation and shaking table concentration. The middlings of the second stage of the spiral separation were classified by grain size of 0.2 mm. The oversize product was milled and the undersize product was sent to the third stage of spiral separation.

Figure 4 presents a flowsheet of the developed technology to produce the hematite concentrate from current tailings.

![flowsheet of separation technology](image)

**Figure 4.** Flowsheet of the separation technology for current tailings.

Table 4 presents the separation characteristics of current tailings with the use of the developed technology.

| Products   | Yield, % | Content of form of iron | Recovery of form of iron |
|------------|----------|--------------------------|--------------------------|
|            |          | Total, % | Hematite, %  | Total, % | Hematite, % |
| Concentrate| 7.2      | 62.2     | 54.5         | 54.6      | 75.4        |
To process a stockpiled tailing, we used a similar technology based on spiral separation and shaking table concentration, but middlings were not milled and final recleaning was conducted by means of High Intensity Magnetic Separation (HIMS) which is widely used for hematite processing [13]. Figure 5 shows a flowsheet of the developed technology.

![Flowsheet of the separation technology for stockpiled tailings.](image)

A distinctive feature of the developed technologies is the rejection of flotation processes [14] and such resource-intensive processes as jigging. The use of spiral separators, which do not consume additional water and electricity [15], helps in the beginning of the process saving resources at the processing plant.

4. Conclusion

We have revealed that the existing technology of hematite recovery from current tailings of Olkon JSC using jigging does not recover fine hematite fractions. This fact leads to significant losses of valuable mineral with plant tailings which are accumulated in a tailings dump. Mineral and chemical analyses of the tailing samples allow us to consider the stockpiled tailing as a mining-induced hematite deposit.

The results of computer simulation of spiral separation showed more efficient recovery of fine hematite fractions from non-magnetic fraction (current tailings) of magnetic separation using this processing method in comparison with jigging machines used at the plant. The conducted industrial tests of spiral separation proved the results of computer modelling and confirmed the feasibility of replacement of jigging machines by spiral separators.

We developed the separation technology for hematite recovery from current and stockpiled tailings. The technology provides for production of hematite concentrate with the content of total iron not less than 62% and recovery of total iron more than 45%.
5. Directions for further research

The results of the study showed that it is possible to recover hematite from the stockpiled tailings, however, a comparison of the indicators presented in Table 4 and Figure 5 shows that separation technology for the stockpiled tailings was less effective than technology for the current tailings. Further research in this area will be related to processing of a representative sample of stockpiled tailings using the technology shown in Figure 4.

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