Combined Column and Mechanical Flotation Cell Process for the Beneficiation of Sanshandao Gold Ore

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ABSTRACT: Semi-industrial tests were conducted to investigate the feasibility and efficiency of a combined column and mechanical flotation cell process for the beneficiation of Sanshandao low-grade gold ore. The results showed that the performance of the combined flotation process of the cyclonic-static microbubble flotation column (FCSMC) and mechanical flotation cells was superior to that of the mechanical flotation cell, while the flowsheet was simplified. FCSMC is efficient when used on fine particles, whereas a mechanical flotation cell is effective for coarse particles. Thus, the combined flotation process exhibited a better separation performance by employing the strengths of both methods. The use of the combined FCSMC and cell flotation process showed promising results for a producing grade of 48.24 g/t gold with 96.13% recovery. The combined column and cell flotation process introduces a new approach for the separation of low-grade gold ore.

1. INTRODUCTION

The gold industry plays an important role in the socio-economic development of China. It has been estimated that 365.34 tons of gold was produced in China in 2020, and China has been the world’s largest gold producer for 13 consecutive years. A total of 301.69 tons were obtained from gold mines, and 63.65 tons were obtained by-products at nonferrous metal mines. Meanwhile, China’s gold consumption reached 820.98 tons in 2020, and this made China the world’s largest gold consumer for 7 consecutive years.

The Sanshandao Gold Mine belongs to the Shandong Gold Group, which has a large resource of gold ore with a low grade of 2.2 g/t. The plant feed tonnage is 4500 tons/day. The flotation circuit consists of a one-stage rougher and a two-stage cleaner with a two-stage scavenger. A concentrate with an average grade of 30.0 g/t gold was obtained using the mechanical flotation cell process, while the total recovery was between 90 and 95%. For the purposes of increasing the production of gold, shortening the process and increasing production efficiency. Therefore, it is necessary to consider some new flotation processes to improve the purification process of low-grade gold ore.

Froth flotation, which is a favorable option for an integral step in gold extraction, has been widely used since the 1930s.1-2 Industrial flotation devices can be grouped into two main categories: columns and mechanical flotation cells.3-9 It is well known that a flotation column has many advantages over a conventional mechanical flotation cell, including simplicity of construction, absence of moving parts, low energy consumption, and low operating and maintenance costs. Many studies have claimed that the flotation column technique yields higher recovery with better grades for fine particles during the cleaner stage.10-13 Meanwhile, several works performed by the authors14,15 have shown that mechanical flotation cells have advantages in recovering coarse particles at rougher or scavenger stages. In recent years, combined column and cell flotation processes have been applied to many mineral beneficiation processes and have improved the overall performance.15,16

During the last three decades, the flotation column technique has been extensively studied, and various columns...
have been developed, including the Leeds column, packed column, Flotare column, hydrochem column, Jameson column, Microcell column, cyclonic column, and cyclo-microbubble column.10,12 Among various flotation columns, the cyclonic-static microbubble flotation column (FCSMC) innovatively adds the cyclone flotation unit onto the conventional bottom of the column flotation unit for physical separation and mineralization further on tailings from the upper unit.17−19 As shown in Figure 1, FCSMC employs cyclonic column flotation separation, cyclone separation, and high-turbulence mineralization. For the column flotation separation, countercurrent mineralization is realized to generate high-quality concentrate from raw materials. Subsequently, cyclone mineralization in the cyclone separation step further separates flotation middling to obtain high-quality tailings. Finally, pipe flow mineralization was used for the separation of cyclone middling and pulp circulation. With higher concentration rates and a simple and efficient flowsheet, the FCSMC has been successfully industrialized for flotation circuits of minerals such as coal and copper ores in China.21−23 However, there have been relatively few studies on the flotation behavior of columns and cells in gold mineral flotation, particularly concerning the combined column and cell flotation process. Therefore, the use of FCSMC for gold ores in pilot or semi-industrial scale studies has high research potential and has a positive effect in promoting the industrial application of FCSMC in gold ore flotation.

In this study, a semi-industrial test was performed using the FCSMC and the mechanical flotation cell to determine the optimum separation conditions for Sanshandao low-grade gold ore. Flotation products were sized to calculate the size-wise grade distribution to investigate the characterization of the column and the cell in low-grade gold ore flotation. The feasibility and efficiency of the combined column and cell flotation process are also discussed in this paper.

2. MATERIALS AND METHODS

2.1. Materials. The auriferous sulfide ore used in this work came from the feed of the flotation circuit at the Sanshandao Plant, Shandong, China. The ore was composed mainly of electrum, pyrite, quartz, sericite, feldspar, calcite, and small amounts of native gold, arsenopyrite, sphalerite, galena, and chalcopyrite. Pyrite was the main Au-bearing mineral. The chemical analysis showed that the typical composition of the ore was 2.28 g/t Au, 10.10 g/t Ag, 3.34% S, 3.83% Fe, 5.64% Al, and 34.59% Si.

Isomyl xanthate and pine oil were used as a collector and a frother, respectively. Isomyl xanthate and pine oil were supplied by Mingzhu Mining Chemicals Co., Ltd. (Hunan, China), and both are of analytical purity.

2.2. Methods. The experiments were conducted with a semi-industrial flotation system at the Sanshandao Plant. The system consisted of a mixing tank, a feeding pump, two circulation pumps, two electric valves, two flotation columns (FCSMC 200 mm × 4000 mm (diameter × height), FCSMC 150 mm × 4000 mm (diameter × height)), and several mechanical flotation cells.

First, the flotation column process with a rougher−cleaner flowsheet was used to determine the optimum conditions (Figure 2) and compare them with the mechanical flotation cell process (a one-stage rougher, a two-stage cleaner, and a two-stage scavenger). The experiments included the determination of optimum parameters in the rougher and cleaner processes and the continuous test. Some constant operating parameters of the flotation column during the experiments are shown in Table 1. A 72 h continuous test was performed with the optimized conditions. The samples of the froth concentrate and tailings from the flotation column process and the mechanical flotation cell process were collected simultaneously.
Table 1. Constant Operating Parameters of the Flotation Column

| Parameter          | Value         |
|--------------------|---------------|
| Solid concentrate  | 45%           |
| Particle size      | 74 μm         |
| Air rate           | 0.6 m³/(m²·min)/0.4 m³/(m²·min) |
| Foam layer thickness | 100 mm/300 mm |

and then analyzed for gold content. The size analysis of the feed, concentrate, and tailings was performed to calculate the size-wise grade distribution of the flotation products in the two processes.

Then, the combined column and cell flotation process was proposed based on the optimum conditions of the flotation column process. As described in Figure 3, it was classified into FCSMC—cell-1 and FCSMC—cell-2 according to the treatment of scavenger concentrate. The process consisted of one rougher stage (FCSMC 200 mm × 4000 mm), one cleaner stage (FCSMC 150 mm × 4000 mm), and one scavenger stage (mechanical flotation cell). Two tests, which lasted at least 8 h each, were performed in a closed circuit and an open circuit. The rougher column and the cleaner column were operated in the optimized conditions. The doses of the collector and the frother used for the scavenger cell were 20 and 10 g/t, respectively. A similar procedure was followed to collect and analyze the samples.

3. RESULTS AND DISCUSSION

3.1. Optimum Parameters of the Flotation Column Process. Figure 4 shows the flotation column results for different reagent dosages. With increasing collector dosage, the gold grade of the concentrate decreased and the recovery of gold first increased and then decreased. When the collector dosage was 80 g/t, the maximum recovery of gold was achieved and the concentrate grade was relatively high at 43.12 g/t. Thus, the collector dosage in the rougher stage was eventually set to 80 g/t. With increasing frother dosage, the concentrate gold grade decreased and the recovery of gold increased. It has been reported by many investigators that the grade of the flotation concentrate decreased when the recovery increased.10,11,14 When the frother dosage increased from 20 to 30 g/t, the recovery of gold was essentially flat (approximately 94.5%). However, the concentrate gold grade at a frother dosage of 20 g/t was much higher than those at 25 and 30 g/t. Thus, the frother dosage in the rougher stage was chosen as 20 g/t.

As the collector or frother dosage increases in the rougher stage, the concentrate grade decreases and the recovery first increases and then either decreases or remains unchanged. With the increase in the amount of the reagent, the floatability of minerals is enhanced and more minerals float into the concentrate, leading to a decrease in grade and an increase in recovery. When the reagent is present in excess, the sharp decrease of selectivity may even cause a decrease in recovery.

Figure 5 shows the flotation column results for different circulations. In a rougher process, the gold grade and recovery of the concentrate first increased and then decreased with increasing circulation pressure. The recovery of gold decreased when the circulation pressure increased from 0.26 to 0.28 MPa; meanwhile, the concentrate grade was significantly higher at 0.26 MPa. Thus, 0.26 MPa was selected as the most appropriate circulation pump pressure for the rougher process. In the cleaner process, the gold recovery of the concentrate increased with the increase of circulation pressure from 0.12 to 0.16 MPa. Upon further increase of the circulation pressure, no further increase of gold recovery was observed; however, a very sharp decrease of the gold grade of the concentrate was registered. The maximum recovery of gold was achieved at 0.16 MPa, and the concentrate grade was relatively high. Thus, the optimum circulation pump pressure in the cleaner process was determined to be 0.16 MPa.

The circulation pressure has an important effect on the FCSMC performance.20 As the circulation pressure increases in the rougher or cleaner process, the gold grade and recovery of the concentrate first increase and then decrease. The increase at a low circulation pressure can be attributed to the increase of mineralization efficiency that is induced by the increase of energy introduced to the system through the enhanced circulation pressure. The decrease of gold grade and recovery occurs at high circulation pressure primarily because the high turbulence of pulp in the flotation column induces a negative effect on the grade and recovery of concentrate.14

Figure 6 shows the flotation column results for different feed rates. The concentrate gold grade increased and the recovery of gold decreased with the increase of the feed rate. When the feed rate varied between 0.42 and 0.58 t/h, the recovery of gold was essentially flat (approximately 94.5%). However, the concentrate gold grade at a feed rate of 0.58 t/h was much higher at 0.42 t/h. To ensure the recovery of gold, a
higher concentrate grade was pursued. Thus, the feed rate was chosen as 0.58 t/h.

The feed rate is related to the residence time and flotation time of pulp in the flotation column that affects the yield of the final product and concentrate grade. The increase in the feed rate causes a decrease in flotation time. Without enough flotation time, only some easy floating minerals float into the concentrate leading to an increase in grade and decrease in recovery.

### 3.2. Comparison of Column and Cell Flotation Performance

Based on the process parameters and operating conditions, which were optimized as described above, a 72 h long continuous separation experiment was conducted. The results of the continuous operation of the flotation column process are shown in Table 2. The flotation results were stable during the continuous test. Gold concentrate with an average grade of 55.26 g/t and 94.49% recovery was obtained via the flotation column process.

The mechanical flotation cell process was examined during the experiments related to the flotation column process, and the flowsheets of the two processes are shown in Figure 7. The comparison results for the two processes are listed in Table 3. The concentrate recovery of the flotation column process was almost the same as that of the mechanical flotation cell process. However, the concentrate grade was significantly higher, namely, 55.26 g/t for the flotation column and 40.46 g/t for the mechanical flotation cell. Moreover, the flowsheet was

| Table 2. Results of the Continuous Test of the Flotation Column Process (Relative Mean Error: within 2%) |
|----------------|----------------|------------|----------------|
| time (h) | feed grade (Au, g/t) | conc. grade (Au, g/t) | tails grade (Au, g/t) | Au rec (%) |
| 0–8 | 1.92 | 50.54 | 0.11 | 94.48 |
| 9–16 | 2.90 | 50.30 | 0.13 | 95.76 |
| 17–24 | 3.23 | 57.27 | 0.16 | 95.31 |
| 25–32 | 2.07 | 76.84 | 0.12 | 94.35 |
| 33–40 | 2.22 | 79.84 | 0.15 | 93.42 |
| 41–48 | 1.62 | 51.06 | 0.11 | 93.41 |
| 49–56 | 1.46 | 39.24 | 0.12 | 92.06 |
| 57–64 | 3.45 | 53.93 | 0.12 | 96.74 |
| 65–72 | 2.05 | 38.33 | 0.11 | 94.91 |
| average value | 2.32 | 55.26 | 0.13 | 94.49 |

**Figure 4.** Effects of (a) collector dosage and (b) frother dosage on the flotation results.

**Figure 5.** Effects of circulation pump pressure on the (a) rougher and (b) cleaner processes on the flotation results.

**Figure 6.** Effects of the feed rate on the flotation results.
It can be seen that the gold grade and distribution treated by FCSMC were higher for the relatively coarse fractions but lower for fraction sizes smaller than 74 μm. For example, for the +154 μm fraction, the gold grade and distribution for FCSMC were 0.12 g/t and 31.66%, while those of the mechanical flotation cell were 0.10 g/t and 26.08%, respectively. In the size range of the −38 μm fraction, the yield treated by the mechanical flotation cell increased by 2.63%, and gold distribution increased by 7.36% compared to FCSMC. These results indicate that the FCSMC is efficient in fine particle separation.

3.3. Performance of the Combined Column and Cell Flotation Process. Based on the different characterization of the column and the cell, the combined process was performed to obtain a better separation performance. The performances of the FCSMC–cell process and the mechanical flotation cell process are compared, and the flotation results are summarized in Table 6. It appears that the overall performance of the FCSMC–cell process is superior to that of the flotation mechanical process. Concentrate grades for FCSMC–cell-1 and FCSMC–cell-2 reached 42.61 and 48.24 g/t, which are increased by 7.98 and 13.61 g/t, respectively, compared to the mechanical flotation cell process. The recovery values for these three flowsheets were 95.90, 96.13, and 95.78%, respectively.

Table 5. Comparison of Size-Wise Grade Distribution in Tailings between the Flotation Column and Mechanical Flotation Cell Processes (Relative Mean Error: within 2%)

| particle size (μm) | yield (%) | grade (Au, g/t) | Au distribution (%) |
|---------------------|-----------|-----------------|---------------------|
|                     | column    | cell            | column              | cell              |
| +154                | 27.84     | 26.62           | 0.12                | 0.10              |
| −154 + 74           | 18.52     | 16.77           | 0.11                | 0.09              |
| −74 + 38            | 18.87     | 19.21           | 0.09                | 0.10              |
| −38                 | 34.77     | 37.40           | 0.10                | 0.11              |
| total               | 100.00    | 100.00          | 0.11                | 0.10              |

It appears that the overall performance of the FCSMC–cell process is superior to that of the flotation mechanical process. Concentrate grades for FCSMC–cell-1 and FCSMC–cell-2 reached 42.61 and 48.24 g/t, which are increased by 7.98 and 13.61 g/t, respectively, compared to the mechanical flotation cell process. The recovery values for these three flowsheets were 95.90, 96.13, and 95.78%, respectively.
Table 6. Comparison of Flotation Performance between the Column Cell Process and the Mechanical Flotation Cell Process

| separation system | grade (Au, g/t) | Au rec (%) |
|-------------------|----------------|------------|
|                   | feed conc. tails rougher tails scavenger conc. | |
| column-cell-1     | 2.53           | 42.61      | 0.11 | 0.12 | 0.76 | 95.90 |
| column-cell-2     | 2.46           | 48.24      | 0.06 | 0.10 | 0.30 | 96.13 |
| cell              | 2.43           | 34.63      | 0.11 |         |      | 95.78 |

Compared with FCSMC–cell-1, the concentrate grade increased by 5.63 g/t, and the tailing grade decreased by 0.05 g/t in FCSMC–cell-2 with the corresponding recovery increasing approximately by 0.23 percentage points. In addition, the rougher tailing grade decreased from 0.12 to 0.11 g/t through scavenging in FCSMC–cell-1, while it decreased from 0.10 to 0.06 g/t in FCSMC–cell-2. Therefore, it indicates that the scavenger concentrate returning to rougher negatively affects the FCSMC–cell process.

Table 7 presents the size analysis of scavenger concentrate in FCSMC–cell-1. The yield and gold distribution of the size fractions coarser than 154 μm were 8.32 and 15.16%, respectively, which is dramatically higher than those of FCSMC concentrate, as shown in Table 3. The negative effect of scavenger concentrate returning to rougher on the FCSMC–cell process can be explained by the following analysis. It is well understood that FCSMC and mechanical flotation cells are inefficient in coarse and fine particles, respectively, and the scavenger concentrate is characterized with typical cell concentrate distributions as determined in the above tests. When the scavenger concentrate returns to the FCSMC rougher, the coarse particles are lost to the tailing and then are recovered to concentrate in the cell scavenger, which leads to the coarse particles in circulation all along. However, in FCSMC–cell-2, coarse particles can discharge to the middling in time to decrease the tailing grade. This function may be responsible for the better performance of FCSMC–cell-2. Thus, this experimental fact indicates that it may be reasonable to return the scavenger concentrate to the grinding or classification stage in the industrial application of the combined process for Sanshandao low-grade gold ore.

4. CONCLUSIONS

Semi-industrial tests were conducted to compare the characterization of the column and cell flotation processes and discuss the feasibility and efficiency of the combined column and cell flotation process. The overall performance of the FCSMC was superior to that of a mechanical flotation cell, while the flowsheet was simplified. FCSMC had advantages in recovering fine particles, whereas the mechanical flotation cell was efficient in recovering relatively coarse particles. The combined FCSMC and cell flotation process for concentrating the Sanshandao low-grade gold ore showed promising results of producing a grade of 48.24 g/t gold with 96.13% recovery. This was mainly because the combined flotation process employs the strengths of both processes. It was found advisable to return scavenger concentrate to grinding or classification but not directly to the FCSMC rougher when the combined process is used in industrial applications. Thus, the combined column and cell flotation process introduces a new approach for the separation of low-grade gold ore.

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### Notes

The authors declare no competing financial interest.

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