*Physicochem. Probl. Miner. Process., 61(3), 2025, 203747* | Physicochemical Problems of Mineral Processing

http://www.journalssystem.com/ppmp | ISSN 1643-1049


# The use of a reflux classifier for chromite ores: assessment of different circuit alternatives at pilot scale

**Ozgur Ozcan**

Hacettepe University Department of Mining Engineering

Corresponding author: ozgurozcan@hacettepe.edu.tr (Özgür Özcan)

**Abstract:** A set of experiments was performed using single replication and a statistical design by using a pilot scale REFLUX™ Classifier (RC300) on three different streams of an operating plant. In the present work, fluidization water rate and pressure set point were considered. Other factors, including feed rate and feed solid content, were maintained constant and were not examined. Based on the mass balanced sampling and pilot scale test results RC can give a similar performance in rejecting gangue from chromite ore compared to the existing spiral circuit. In addition to this, different concentrates can be obtained with a wide recovery/grade range by adjusting the main operational parameters. RC can produce a pre concentrate which is a grade of 18.35 $Cr_2O_3$ with a 43.40% mass recovery and 87.50% chromite recovery which is very close to the performance of existing circuit. The chromite grades of sample C clearly show that the final concentrate can be upgraded by using a finishing RC. The chromite recovery comparison between the fine table and RC 300 (high grade) clearly shows that the separation mechanism and the existence of parallel inclined plates positively affect the fine particle recovery. According to the results, a new flowsheet can be designed by using the spirals and the RC. This would eliminate the need for both shaking tables and dragon tables and the required footprint. The test results revealed that RC could be suitable device as a pre-concentration and final concentration operations in chromite beneficiation plants.

*Keywords:* Reflux™ Classifier, chromite ore, gravity concentration, teetered bed separator

## 1. Introduction

Low-grade chromite ores globally are extracted and processed by various gravity concentration techniques. Various beneficiation methods have been applied to chromite ores, ranging from gravity concentration to flotation (Burt and Mills, 1984; Tripathy et al., 2015a; Wesseldijk et al., 1999; Young and Luttrell, 2012). Izerdem (2024), discussed significance of processing low-grade and fine chromite, and advancements in separation methods in detail. A multitude of research in mineral processing have concentrated on the recovery efficiency of chromite, with numerous methodologies for this objective elaborated upon comprehensively. The study focused on providing information on low-grade Cr ore treatment, particularly in spiral concentrators, and their added value, with Türkiye as the study area (Izerdem, 2024).

Density-based separations are the most efficient and economical techniques for chromite beneficiation (Izerdem, 2024). A standard chromite beneficiation flowsheet comprises the crushing, screening, and wet milling of the ore. Classification by wet-screening, followed by de-sliming using hydrocyclones, constitutes the predominant circuit for low-grade ores. Dense medium cyclones for coarse processing (Harzanagh et al., 2017), or spiral circuits and tabling (Murthy and Tripathy, 2020) are the conventional beneficiation methods.

Evaluating the efficacy of density-based separation techniques is a persistent difficulty in mineral processing applications, especially for high-density materials. Numerous research has shown that gravity separation is a well-established method for chromite recovery (Ozyurt et al., 2023; Altın et al., 2018; Mokeona et al., 2020; Khakmardan et al., 2020). In recent years, the teetered or hindered bed separators have gained favour in enhancing classification and separation efficiency. Hydraulic

DOI: 10.37190/ppmp/203747

classifiers have developed into several kinds of equipment in the industry, each with distinct commercial designations: Floatex Density Separator (FDS), Cross Flow Separator (CFS), Reflux Classifier (RC), and Allflux Classifier (AC), among others. These units have been employed in mineral sand (Zhou et al., 2006; Tripathy et al., 2015a), low-grade iron ore (Amariei et al., 2014), chromite (Kari et al., 2006), pyrite (Remes et al., 2011), and the coal preparation sector (Hyde et al., 1988; Mankosa et al., 1995; Das et al., 2009; Sarkar et al., 2008).

The reflux classifier (RC) is an innovative hydraulic separator that combines a fluidized bed (vertical section) with a lamella settler (inclined section) to separate particles based on size and density. It operates similarly to a hindered settling column or a teetered bed separator (TBS) (Galvin et al., 1999), where slower-settling particles report to the overflow and faster-settling particles to the underflow. The vertical section primarily relies on hindered settling, where separation is governed by the terminal velocities of particles, which are influenced by their size and density. However, this component alone is less effective in differentiating fine heavy particles from coarse light particles with similar terminal velocities. The inclined section addresses this limitation by expanding the sedimentation surface area, enhancing throughput beyond conventional systems (Galvin et al., 2002; Galvin et al., 2009). This design significantly improves separation efficiency compared to traditional classifiers (Amariei et al., 2014). Fig. 1 provides a schematic illustration of the RC.

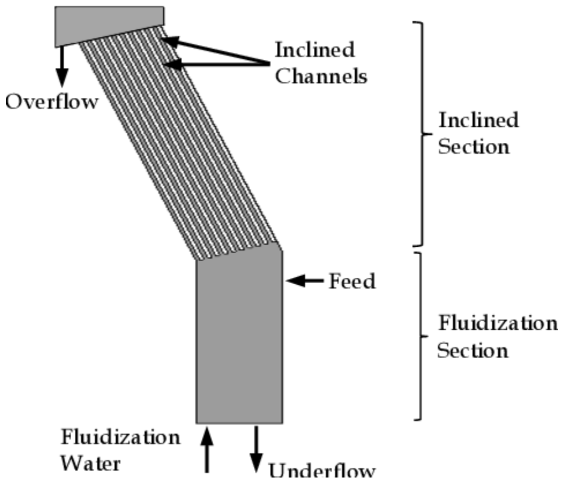


Fig. 1. Schematic of the Reflux Classifier (Galvin et al., 2009)

The reported literature emitted wide range of study on conventional chromite beneficiation techniques and their comparisons. However, currently, the novel technologies like teetered or hindered bed separators have a big potential to pre-concentration methods or alternatives to gravity separation for chromite minerals.

This publication outlines the first pilot-scale experiment of the RC at a chromite concentration plant in Türkiye. The primary objective of this research is to provide a collection of findings acquired by a pilot-scale RC, often referred to as the RC300. The device was used to examine prospects for enhancing grade and yield at the operational spiral-shaking table circuits, as well as for the forthcoming expansion project. The primary objective of the research was to ascertain the correlation between operational factors and performance metrics of the chromite concentration device, its operational consistency, and its responsiveness to variations in operating circumstances inside a functioning chromite beneficiation plant.

## 2. Experimental

### 2.1. Chromite beneficiation plant

Fig. 2 illustrates the simplifying flowsheet of the facility, including test streams and all sampling locations. In the beneficiation circuit, the screen undersize stream is sent to the de-sliming cyclone, where the cyclone overflow is discarded as slime. The cyclone underflow stream is subsequently transferred to the spiral concentration circuit to produce a pre-concentrate. The spiral concentration circuit comprises a rougher, a scavenger, and two stages of cleaner spirals. The output of the spiral concentration circuit is referred to as spiral tailing. Subsequently, the spiral concentrate was sent to an innovatively built hydraulic classifier, a teetered bed separator (TBS), to provide two narrow size fractions for the shaking table circuit. The TBS underflow is sent to coarse tables, whereas the TBS overflow stream is directed to fine tables. The total table concentrate is around 40-42% $Cr_2O_3$ fed to dragon tables, where by use of manual labour, the material is upgraded to 42-44% $Cr_2O_3$.

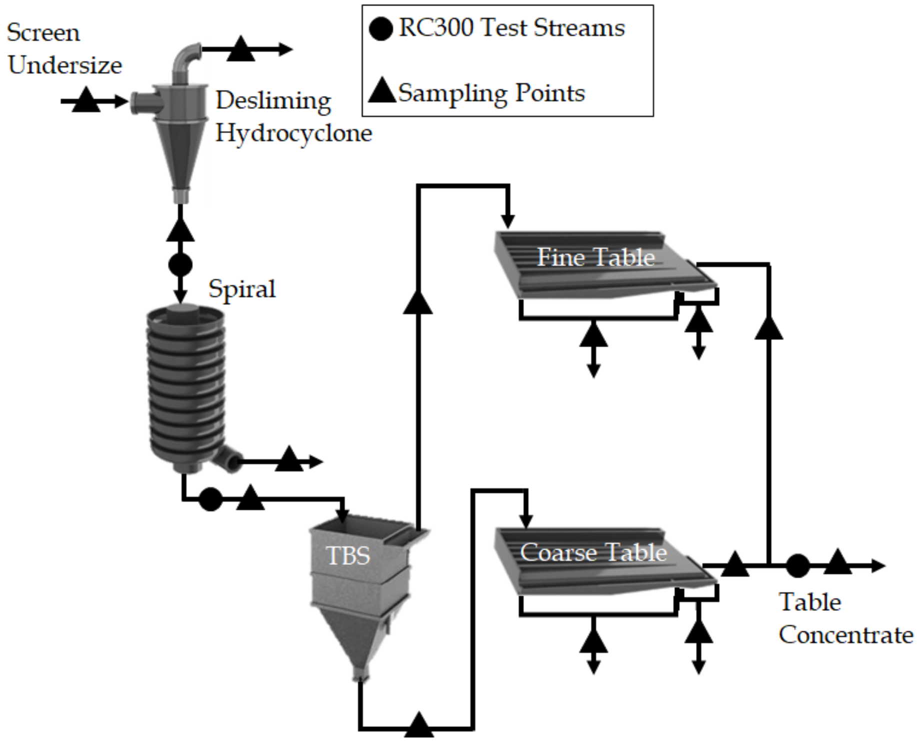


Fig. 2. Simplified flowsheet of chromite concentration plant and test streams

## 2.2. Performance evaluation of the actual plant

In order to evaluate the performance of actual plant and unit operations, a sampling study was carried out in the gravity concentration circuit. To obtain the data required for the determine the existing flowrates and grade/recovery values and for the comparison with RC300 test results representative samples were collected around the circuit. Using the measured tonnages and chromite analysis of the samples, the mass balance was determined. The effects of the reflux classifier application on the existing circuit were quantitatively determined.

## 2.3. Pilot scale reflux classifier (RC300)

A pilot-scale Reflux Classifier (RC300) was utilized, comprising a series of parallel inclined channels positioned above a fluidized bed. The RC300 is a pilot-scale unit designed to process the equivalent of one spiral start, meaning it has a processing capacity comparable to that of a single trough in an industrial scale spiral concentrator. RC 300 is engineered for in-plant testing in coal and mineral applications. Throughput typically ranges from 1 ton per hour (tph) to 5 tph, contingent upon the type and size of the feed material. The inclined section comprised channels with a length of 1.2 m, oriented at an angle. A configuration comprising 38 channels was established utilizing 37 plates. A fluidized bed with a cross-sectional area of approximately 0.300 m × 0.300 m was positioned beneath the inclined section. Two pressure sensors were employed to quantify the suspension density along the vertical fluidized bed section, establishing a foundation for regulating the product discharge rate to the underflow. A fluidization water (FW) also named as teetered water (TW) chamber was installed above the fluidized bed section to distribute the spray water using a spray nozzle with a diameter of 2.5 mm. The distance between the inclined channels measures 6 mm (Galvin et al., 2009).

### 2.4. Sample characterization

Three streams were evaluated using the RC300 from FLSmidth-Ludowici. Sample A consisted of spiral circuit feed, while sample B comprised spiral concentrate, and sample C was derived from shaking table concentrate (Fig. 2). A comprehensive sampling campaign was conducted prior to the pilot scale study to collect RC300 feed samples. A prolonged sampling period was conducted to obtain representative samples for each stream. The sampling campaign was conducted over an 8-hour shift. Approximately 15 $m^3$ of each sample was collected at the original solid content to conduct the RC tests.

### 2.5. Reflux classifier tests

Fig. 3 displays the flowsheet utilized for the RC testing. A uniform pulp with original solid content was prepared in the tank and thereafter transferred to the RC unit at a consistent flow rate using an adjustable speed pump. The flow rates of water fluidization were modified to range from 0.8 to 1.3 $m^3/h$ based on $Cr_2O_3$ grades. Each sample was subjected to six tests. During each test, representative samples were collected from both the concentrate and tail streams at regular intervals of about 30 seconds under stable conditions. Subsequently, all products were analysed for $Cr_2O_3$ analysis.

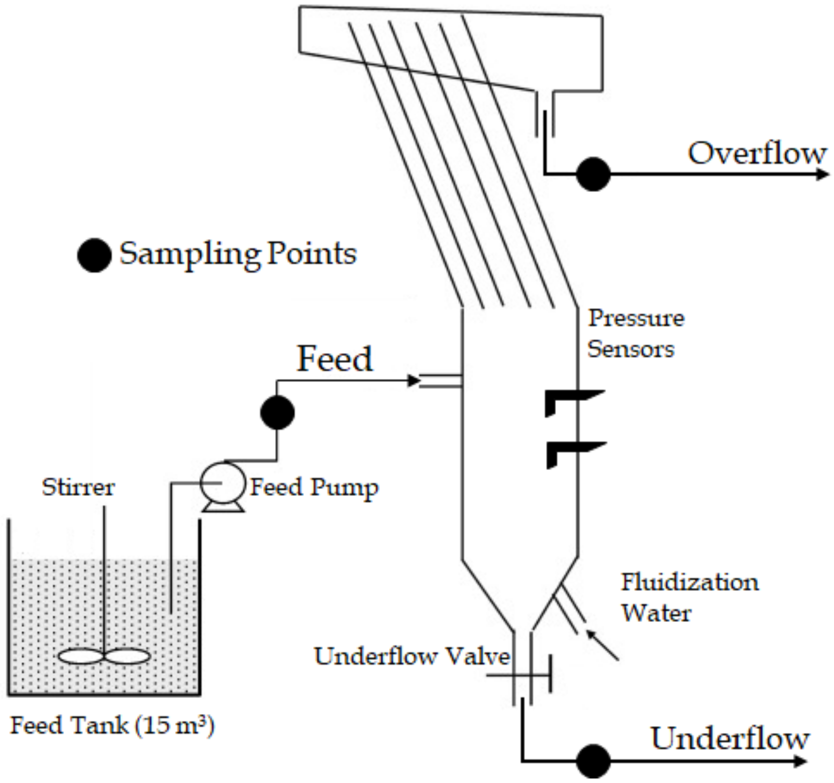


Fig. 3. Simplified flowsheet for the Reflux Classifier tests

The RC tests were conducted at about 2 tons per hour of dry feed tonnage. The equipment brochure (REFLUX™ Classifier, 2024) indicates that this capacity is about 80% of the solid capacity of the RC300 HC at -300+75 μm. During the testing, the density set point and fluidization rate were changed. The RC300 machine operated using an automated PI controller configured to sustain the average density in the column at a predetermined value. During the testing, the control unit initially maintains the underflow valve in a closed position, resulting in the accumulation of coarse, dense particles inside the unit, while fine, less dense material is expelled by the overflow. The pulp density progressively rises until the predetermined point is reached, at which point the underflow valve begins to open.

Upon achieving a steady state, simultaneous stream samples of the overflow and underflow were obtained, followed by a sample of the feed. Altering the set point required more than 20 minutes for the density to become stable; it was presumed that steady-state functioning was achieved after an additional 20-minute interval. The full conditions of study for all samples are listed in Table 1.

Table 1. Pilot scale RC test conditions

| Test No. | Sample A | | Sample B | | Sample C | |
|---|---|---|---|---|---|---|
| | Density set point (kg/m³) | Fluidization Rate (m³/h) | Density set point (kg/m³) | Fluidization Rate (m³/h) | Density set point (kg/m³) | Fluidization Rate (m³/h) |
| 1 | 1500 | 0.8 | 1700 | 0.9 | 1700 | 1.0 |
| 2 | 1700 | 0.8 | 1900 | 0.9 | 1900 | 1.0 |
| 3 | 1900 | 0.8 | 2100 | 0.9 | 2100 | 1.0 |
| 4 | 1500 | 1.2 | 1700 | 1.2 | 1700 | 1.3 |
| 5 | 1700 | 1.2 | 1900 | 1.2 | 1900 | 1.3 |
| 6 | 1900 | 1.2 | 2100 | 1.2 | 2100 | 1.3 |

## 3. Results and discussion

### 3.1. Sample characterization

The key features of the RC feeds (samples A, B, and C) are presented in Table 2. It illustrates that sample A exhibits the coarsest size, while sample C has the finest. Sample C had the highest $Cr_2O_3$ concentration, as anticipated. For the sake of clarity in this study, the tests of $Cr_2O_3$ indicate the only precious mineral. The grades and distributions of fractional $Cr_2O_3$ in test samples are shown in Fig 4. As seen in Fig. 4, chromite distribution is between the size fractions of -425+38 µm. $Cr_2O_3$ grades increase as size fractions decrease for each sample. This situation reveals the importance of recover of fine chromite from low-grade ore.

Table 2. Key features of the RC test samples

| Sample Name | Density (g/cm³) | $P_{80}$ (µm) | Solid (%) | Grade (%) | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | $Cr_2O_3$ | $Fe_2O_3$ | $Al_2O_3$ | MgO | $SiO_2$ | CaO |
| A (Spiral Feed) | 3.52 | 348 | 35.45 | 9.10 | 9.52 | 1.89 | 37.05 | 30.06 | 0.92 |
| B (Spiral Concentrate) | 3.96 | 295 | 40.18 | 18.70 | 10.70 | 1.02 | 30.08 | 28.46 | 0.57 |
| C (Table Concentrate) | 4.52 | 255 | 28.16 | 40.46 | 13.46 | 0.67 | 23.43 | 17.39 | 0.24 |

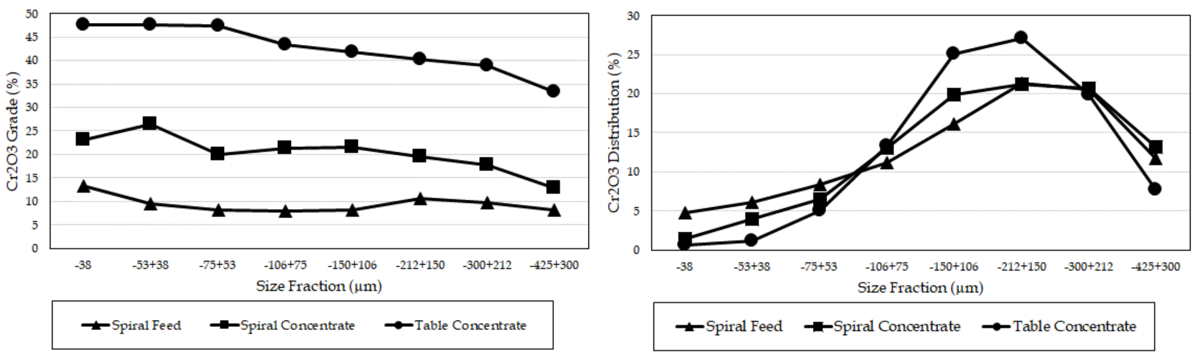


Fig. 4. Fractional $Cr_2O_3$ grade and distribution of RC test samples

### 3.2. Performance evaluation of the actual plant

Solids and $Cr_2O_3$ mass balance of the beneficiation circuit were determined using experimental data. For this purpose, the mass balance software JKSimMetv6.0.1 was used. The calculated values align well with the experimental data, indicating the success of the sample survey. (Fig. 5). The balanced solids tonnage, elemental $Cr_2O_3$ assay and recovery distributions around the circuit during the sampling survey are summarized in Table 3.

Table 3. Solid mass balance values of plant with $Cr_2O_3$ assays and recoveries

| Stream | Weight (tph) | $Cr_2O_3$ (%) | Recovery (%) | $P_{80}$ (µm) |
|---|---|---|---|---|
| Screen Undersize | 240.86 | 8.47 | 100.00 | 366 |
| Cyclone O/F (Slime) | 23.23 | 2.57 | 2.93 | 39 |
| Spiral Feed | 217.63 | 9.10 | 97.07 | 348 |
| Spiral Tail | 125.48 | 2.05 | 12.61 | 398 |
| Spiral Conc. | 92.15 | 18.70 | 84.47 | 295 |
| TBS U/F | 48.36 | 20.87 | 49.48 | 366 |
| TBS O/F | 43.79 | 16.30 | 34.99 | 202 |
| Coarse Table Tail | 26.13 | 4.88 | 6.25 | 379 |
| Coarse Table Conc. | 22.23 | 39.68 | 43.23 | 308 |
| Fine Table Tail | 33.84 | 8.69 | 14.41 | 245 |
| Fine Table Conc. | 9.95 | 42.20 | 20.58 | 149 |
| Total Conc. | 32.17 | 40.46 | 63.80 | 255 |
| Total Tail | 208.69 | 3.54 | 36.20 | 385 |
| Feed | 240.86 | 8.47 | 100.00 | 366 |

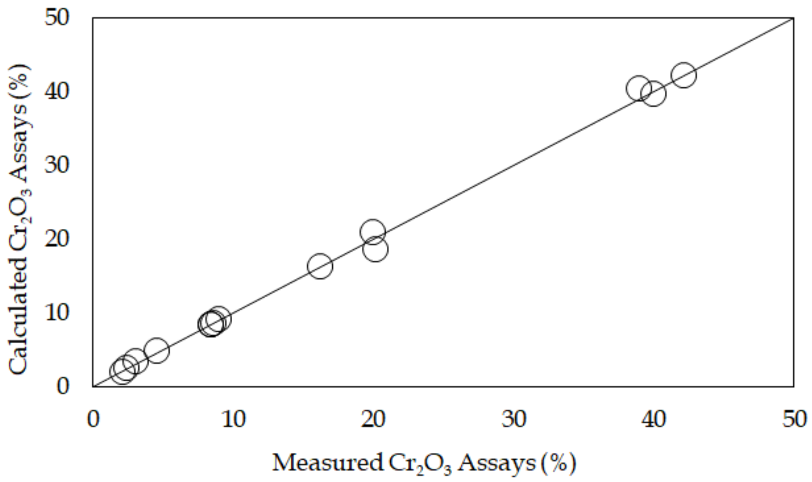


Fig. 5. Comparison of measured and mass balanced $Cr_2O_3$ assays plotted along the y = x line

Table 3 shows that the final chromite concentrate was produced at a grade of 40.46% $Cr_2O_3$ and recovery of 63.80% during the plant sampling period. Approximately 36% of the chromite is also lost from the final tail from cyclone overflow, spiral tail and table tailings. Chemical examine indicates that the chromite concentration in tailings ranges from 2.05% to 8.69%, with the fine table tail exhibiting the greatest chromite grade. The -40 µm size fraction comprises roughly 80% of the weight of the cyclone overflow. When two high tonnage tails (spiral tail and table tails) are evaluated for chromite. According to survey results, the 34.84% of $Cr_2O_3$ in the plant tail loss in the spiral circuit and 57.08% of $Cr_2O_3$ in the plant tail loss in table circuit are remarkable. Fig. 2 indicates that the quantity of the finer fraction is minimal in the spiral and coarse table circuit due to the processes of de-sliming and hydraulic classification.

Unit mass and chromite recoveries of spiral circuit is higher than total table circuit (Table 5). In terms of unit recoveries, it is clear from Table 5 that fine tables are less efficient in fine-particle recovery under the optimum operational conditions. In the coarse streams including spiral and coarse table mass and chromite recoveries are higher. This clarifies the significance of eliminating the slime fraction and sorting materials into narrow size/density classes to enhance the recovery of conventional gravity equipment, such as spirals and shaking tables, as well as the detrimental impact of fine and ultrafine particles on the separation performance of shaking tables.

Table 5. Unit recovery values of actual plant during sampling campaign

| Unit Operation | Mass Recovery (%) | Chromite Recovery (%) |
|---|---|---|
| De-sliming | 90.35 | 97.07 |
| Spiral Circuit | 42.34 | 87.01 |
| Coarse Table Circuit | 45.96 | 87.37 |
| Fine Table Circuit | 22.71 | 58.81 |
| Table Circuit (Total) | 34.91 | 75.54 |
| Plant Recovery | 13.36 | 63.80 |

### 3.3. Reflux classifier tests

Table 6 displays the findings of the mass-balanced RC tests conducted on samples A, B, and C. Table 3 indicates that the studied samples were concentrated up to 43.50% $Cr_2O_3$ for sample A, 46.18% $Cr_2O_3$ for sample B and 53.91% $Cr_2O_3$ for sample C respectively. The RC underflow chromite recovery decreases significantly depending on the increase in fluidization water rate (FW) and density set point (SP) for all samples. The increased FW and SP led to a significant beneficiation of chromite in the RC underflow. Furthermore, certain O/F products exhibited acceptable $Cr_2O_3$ losses: below 5% for sample A and below 8% for sample B.

The $Cr_2O_3$ analyses of sample A revealed that a feed grade of 9.10% $Cr_2O_3$ could be concentrated up

Table 6. Pilot scale RC test results

| Sample ID | Test Nr. | Feed $Cr_2O_3$ (%) | Underflow (U/F) Mass (%) | Underflow (U/F) $Cr_2O_3$ (%) | Underflow (U/F) Recovery (%) | Overflow (O/F) Mass (%) | Overflow (O/F) $Cr_2O_3$ (%) | Overflow (O/F) Recovery (%) |
|---|---|---|---|---|---|---|---|---|
| A | 1 | 9.10 | 43.40 | 18.35 | 87.50 | 56.60 | 2.01 | 12.50 |
| | 2 | | 29.38 | 24.20 | 78.12 | 70.62 | 2.82 | 21.88 |
| | 3 | | 21.41 | 29.99 | 70.56 | 78.59 | 3.41 | 29.44 |
| | 4 | | 37.13 | 20.18 | 82.32 | 62.87 | 2.56 | 17.68 |
| | 5 | | 15.56 | 35.87 | 61.31 | 84.44 | 4.17 | 38.69 |
| | 6 | | 10.79 | 43.50 | 51.58 | 89.21 | 4.94 | 48.42 |
| B | 1 | 18.70 | 78.73 | 22.35 | 94.11 | 21.27 | 5.18 | 5.89 |
| | 2 | | 55.20 | 28.97 | 85.53 | 44.80 | 6.04 | 14.47 |
| | 3 | | 34.97 | 40.08 | 74.96 | 65.03 | 7.20 | 25.04 |
| | 4 | | 65.22 | 25.25 | 88.08 | 34.78 | 6.41 | 11.92 |
| | 5 | | 44.56 | 33.04 | 78.74 | 55.44 | 7.17 | 21.26 |
| | 6 | | 27.94 | 46.18 | 69.02 | 72.06 | 8.04 | 30.98 |
| C | 1 | 40.46 | 83.05 | 46.18 | 94.79 | 16.95 | 12.44 | 5.21 |
| | 2 | | 73.17 | 49.29 | 89.14 | 26.83 | 16.38 | 10.86 |
| | 3 | | 65.18 | 51.63 | 83.18 | 34.82 | 19.55 | 16.82 |
| | 4 | | 77.63 | 47.63 | 91.39 | 22.37 | 15.58 | 8.61 |
| | 5 | | 68.31 | 50.91 | 85.95 | 31.69 | 17.94 | 14.05 |
| | 6 | | 58.98 | 53.91 | 78.59 | 41.02 | 21.12 | 21.41 |

to a salable product grade of 43.50% $Cr_2O_3$. Results also showed that concentrate grade increases with increasing SP while recovery decreases. At the optimum set point of 1500, the mass yield to u/F was 43.40% at a tailing grade of 2.01% $Cr_2O_3$ and the concentrate grade of 18.35% $Cr_2O_3$.

The $Cr_2O_3$ analyses of Sample B revealed that a feed grade of 18.70% $Cr_2O_3$ could be concentrated up to a concentrate grade of 46.18% $Cr_2O_3$. The underflow mass yield at the optimum set point of 1700 was 78.73% at a tail grade of 5.18% $Cr_2O_3$.

The $Cr_2O_3$ analysis of sample C revealed that a feed grade of 40.46% $Cr_2O_3$ could be concentrated a product grade between 46-54% $Cr_2O_3$. The U/F of RC had a mass yield between 58.98-83.05%. The optimum results were obtained where the RC received a feed of 40.46% $Cr_2O_3$ producing a salable concentrate 46.18% $Cr_2O_3$ with a mass yield of 83.05% and a recovery of 94.79%. These high mass and chromite recoveries can be a sign of effective removal of free gangue minerals related to imperfection of conventional circuit.

To ascertain the interactional effects of studied operational factors on performance parameters, the interaction between operational factors (TW, SP) and efficiency parameters was modelled as a partition surface using MATLAB software. The plots of yield to underflow as a function of TW and SP is shown in Fig. 6.

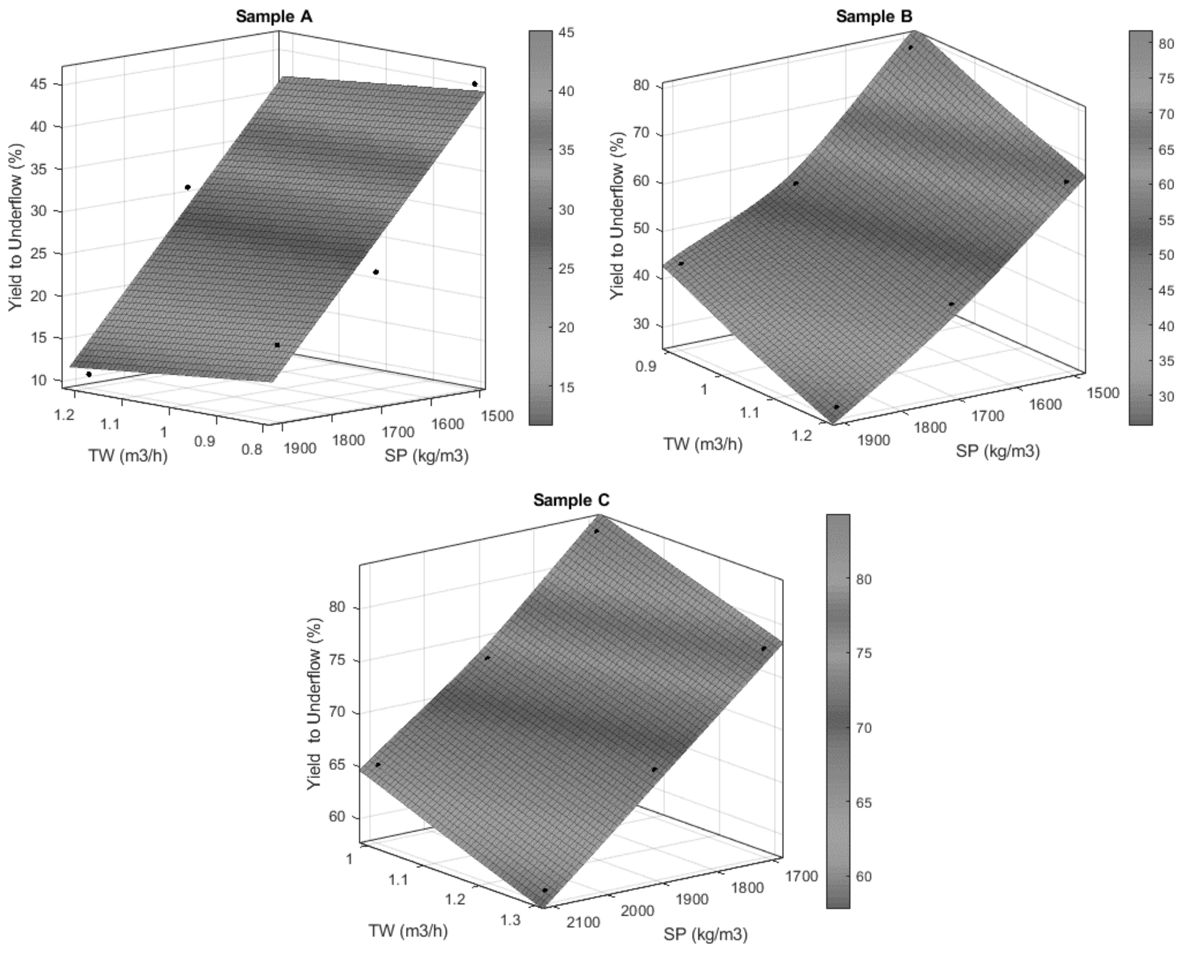


Fig. 6. Effect of TW and SP operational parameters on yield to underflow

Experimental results indicated a predominantly linear correlation between the examined operational parameters and yield to underflow across all samples. The yield to underflow declines as TW and SP increase. Maximum yield to underflow can be attained by sustaining low pressure and water levels. The rising water speed, which is based on the teeter water flow rate and the cross-sectional area of the separation division, is the opposite of the particles falling settling speeds. The overflow channel receives particles entering the column with a settling velocity lower than the upward velocity. With the rise in teeter water velocity, more amount of solids reports to the overflow stream in turn decreasing the yield to the underflow (Sarkar, 2008). Similarly, as the SP increases, the bed height also increases in the column. Therefore, more packed and viscous bed prevents material motion to the underflow. In this case, only coarser and heavier (denser) particles are directed tounderflow and more amount of particles are directed to overflow.

Fig. 7 illustrates the relationship between the U/F $Cr_2O_3$ grade and the variables TW and SP. Fig. 7 illustrates that, as the TW and SP increases, the U/F $Cr_2O_3$ grade also increases. SP has major effect on the U/F $Cr_2O_3$ grade, followed by TW for the studied ore. The highest grade can be obtaining by maintaining highest levels of both variables. It is known that The SP defines the collection of deposited particles within the unit, thereby influencing the bed height in hindered bed separators. The height of the bed is directly proportional to the SP. With an increase in bed height, there is a corresponding rise in the average density and viscosity of the suspension, which enhances the degree of resistance encountered by the particles during the settling process. In this condition less material can be report to U/F and these particles have a higher density and $Cr_2O_3$ grade.

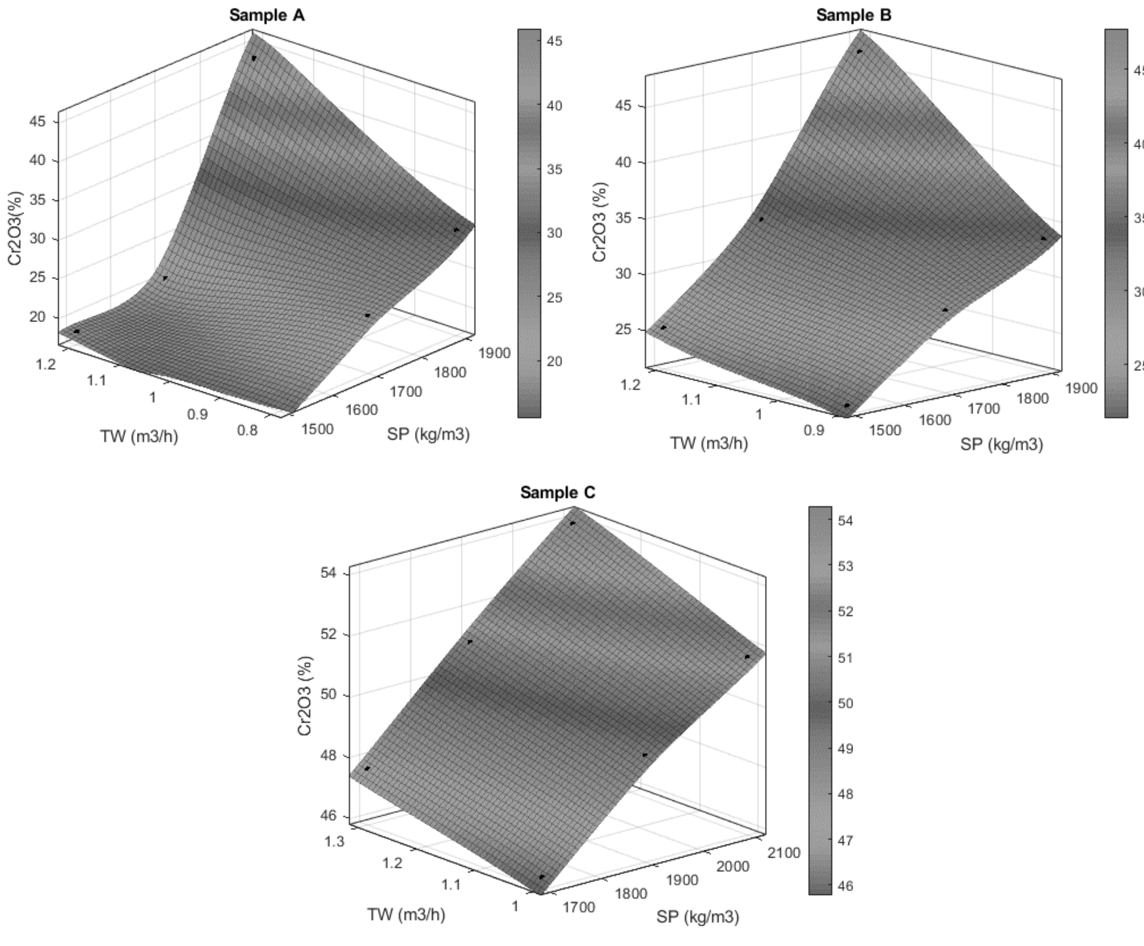


Fig. 7. Effect of studied process variables on U/F $Cr_2O_3$ grade

Fig. 8 illustrates the relationship between U/F $Cr_2O_3$ recovery and the variables TW and SP. Fig. 8 illustrates that, as the TW and SP increases, the U/F $Cr_2O_3$ recovery decreases, while $Cr_2O_3$ grade increases with the TW and SP. At lessened bed pressures, hindered bed classifiers function solely as classifiers (Das et al., 2009), resulting in only the finer and fewer dense particles reporting to the overflow. On the contrary, at high SP, the suspension is denser and increased TW enhances the upward hydraulic transfer force. Furthermore, denser particles with higher chromite content may be sent to the overflow regardless of the SP. The comparative displacement of fine particles to the underflow is decreases because of more closed bed and higher upward hydraulic transport force which results some of the fine and locked chromite particles to move O/F and decreased recovery in the U/F.

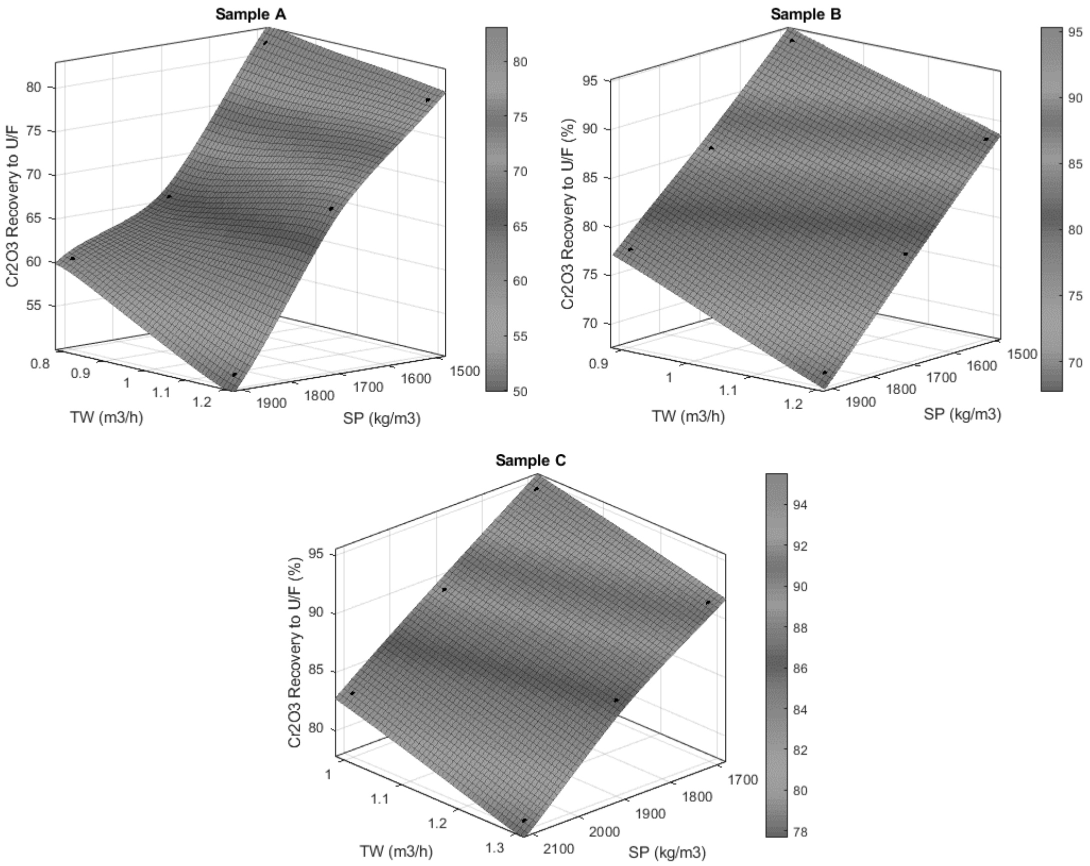


Fig. 8. Effect of studied process variables on U/F $Cr_2O_3$ recovery

## 4. Conclusions

Graphing the test findings at the U/F in relation to the SP for samples indicates that the mass yield and $Cr_2O_3$ recovery decreased, while $Cr_2O_3$ grade increased with the SP followed by TW. The observed decline in U/F mass recovery with the increase in SP and TW may be solely linked to the removal of gangue from the concentrate. It is revealed that the experimental conditions at intermediate and higher SP values were more effective in conveying chromite to the underflow and gangues to the overflow. An additional rise of the SP to 1900 kg/m$^3$ resulted in a U/F product exhibiting the highest $Cr_2O_3$ grade, potentially accompanied by less gangue grades across all samples. The lower mass recovery at U/F recorded above these SP values can be attributed not only to gangue removal but also loss some of the finer chromite particles to O/F. This is also reflected to U/F $Cr_2O_3$ recovery, for which a significant decrease was observed.

Density-based separation is shown to be more successful at a fluidization water rate (FW or TW) less than 1 m$^3$/h/m$^2$. The rise in TW reduced either yield to U/F as well as $Cr_2O_3$ recoveries at the U/F across all samples. In teetered beds, particles separate based on density rather than size when fluidization water rate are low. However, when fluidization water rate rise, the effect changes in the opposite direction (Galvin, 2003; Moritomi et al., 1982). Galvin (2003) demonstrated that a dense suspension forms at lower superficial fluid movement, with finer high-density particles positioned underneath coarser low-density particles. With a rise in fluidization velocity, the bed exhibits enhanced mobility (Galvin et al., 2005), resulting in blending. So, since the fluidization water rate plays a crucial role, the ore's properties, especially its size, grade, and amount of near-density material, should be analyzed to find the optimum value. Doroodchi et al. (2006) reported similar findings in their coal research.

Performance evaluation of RC test results and its comparison with spiral and table circuits is given in Fig. 9. Criteria used for comparing process performance of RC and existing circuit included unit recovery and grade.

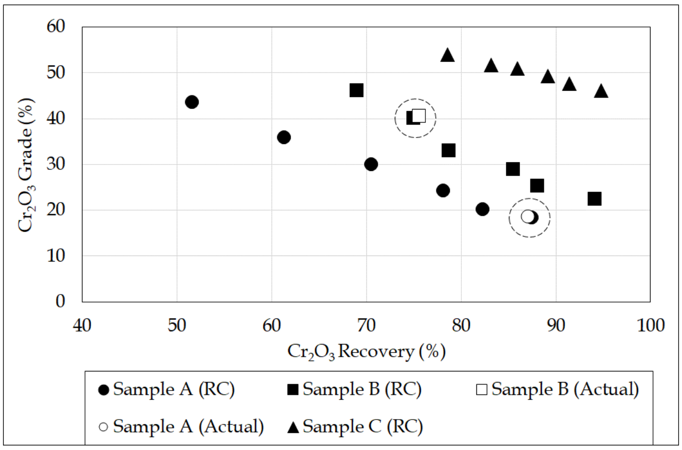


Fig. 9. Performance evaluation of RC test results and its comparison with spiral and table circuit

Sampling survey results indicated that spiral circuit of existing plant has a 42.34% mass recovery and 87.01% chromite recovery during sampling campaign (Table 5). According to Fig. 9, RC can give a similar performance in rejecting gangue from chromite ore compared to the existing spiral circuit. In addition to this, different concentrates can be obtained with a wide recovery/grade range by adjusting the main operational parameters. RC can be produce a pre concentrate which is a grade of 18.35 $Cr_2O_3$ with a 43.40% mass recovery and 87.50% chromite recovery which is very close to performance of existing circuit. The chromite grades of sample C clearly shows that the final concentrate can be upgrade by using a finishing RC.

According to test results, obtain a pre-concentrate is possible with an alternative circuit including RC instead of multi stage spiral. The comparison of existing and alternative flowsheet is given in Fig. 10. Their performance in comparison is shown in Table 7. This pre-concentration alternative can provide similar results to multi stage spiral concentration circuit. As observed from Table 7, a high-grade pre-concentrate can be achieved in both concentrate mass pull and chromite recovery.

Even though the spiral is simple in design, the fluid properties are made even more complicated by a second flow that acts radially inside the channel. Entrainment limits spiral concentrators by preventing them from achieving the desired concentrate grade in a single stage. On the other hand, hindered settling conditions in the RC increases the influence of density while diminishing the influence of particle size. For this reason, a hindered bed separator like RC, can eliminate complex spiral separation stages and to reduce the footprint of the circuit.

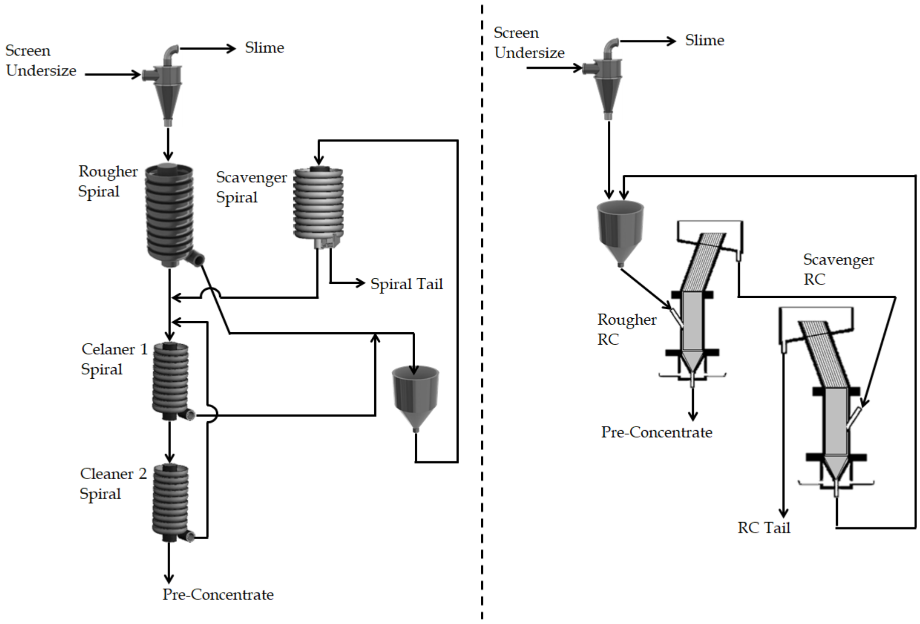


Fig. 10. Simplified flowsheet of existing (left) and alternative (right) circuits to obtain pre concentrate

Pilot scale test results also revealed that an alternative circuit including RC instead of a complex shaking table circuit can be feasible to produce a high-grade concentrate. Fig. 11 illustrates the comparison between the current table circuit and the alternative flowsheet. The performance comparison is tabulated in Table 8.

Table 7. Performance comparison of existing spiral circuit and RC300

| Performance Parameter | Spiral Concentration Circuit | Pilot Scale RC300 |
|---|---|---|
| Mass Recovery to Conc. (%) | 42.34 | 43.40 |
| $Cr_2O_3$ (%) | 18.70 | 18.35 |
| $Cr_2O_3$ Recovery (%) | 87.01 | 87.50 |

Table 8. Performance comparison of existing shaking table circuit and RC300

| Performance Parameter | Coarse Table Circuit | Fine Table Circuit | Table Circuit (Total) | Pilot Scale RC300 | Pilot Scale RC300 (High Grade) |
|---|---|---|---|---|---|
| Mass Recovery to Conc. (%) | 45.96 | 22.71 | 34.91 | 34.97 | 27.94 |
| $Cr_2O_3$ (%) | 39.68 | 42.20 | 40.46 | 40.08 | 46.18 |
| $Cr_2O_3$ Recovery (%) | 87.37 | 58.81 | 75.54 | 74.96 | 69.02 |

Fig. 9 and Table 8 indicated that pilot scale RC can produce a wide range of product with varying grade and recovery values. According to pilot scale test results RC can produce a concentrate with similar product specifications with existing circuit. Furthermore, the product specifications can easily be changed by adjusting SP and TW. The chromite recovery comparison between fine table and RC 300 (high grade) clearly shows that separation mechanism and the existence of parallel inclined plates positively affect the fine particle recovery. The parallel inclined plates significantly increase sedimentation surface. This configuration is appropriate for hydrosizing as well as gravity separation processes. It should be noted that the pilot scale tests conducted with sample B (spiral concentrate) were performed before hydraulic classification. An alternative flowsheet design with hydraulic classification has a potential to increase fines recovery in RC circuit (Fig. 11).

Shaking table concentration, the primary approach of chromite beneficiation and frequently preferred by plants (Izerdem, 2024). Nevertheless, shaking tables exhibit some deficiencies, including inadequate operating stability, extensive floor space requirements, and limited processing throughput

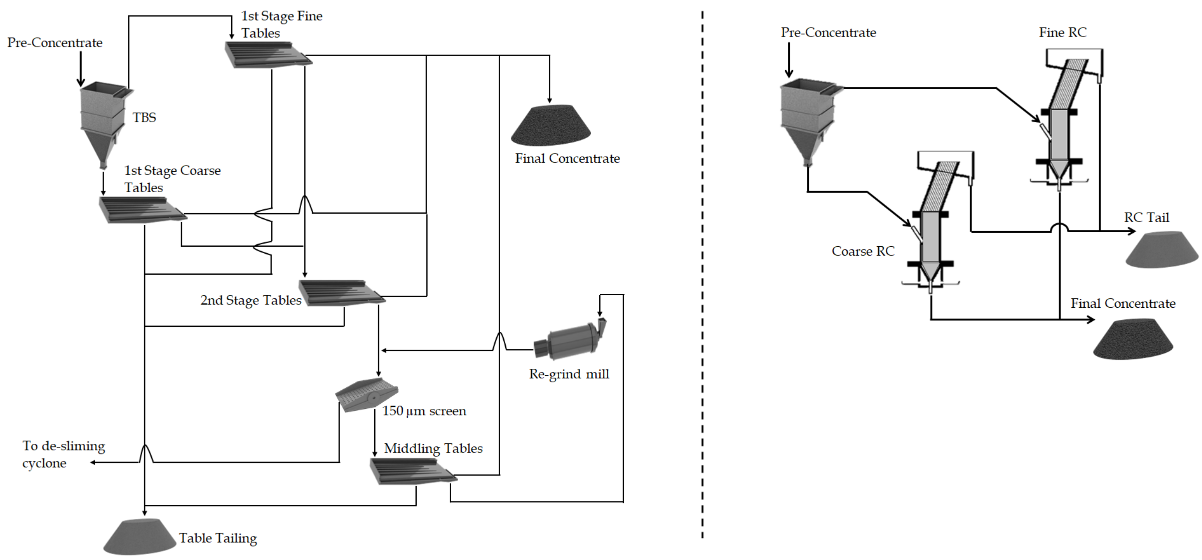


Fig. 11. Simplified flowsheet of existing (left) and alternative (right) circuits to obtain final concentrate

of the bed surface and large water consumption. Furthermore, shaking tables require a steady flowrate of both water and solids as well as frequent monitoring, inspection, and adjustment during operation (Gupta and Yan, 2006; Wills and Finch, 2015; Dehghani et al., 2018). The quantity of shaking tables for the coarse and fine circuit are 40 and 40, respectively in the existing plant. This means to a total of 80 shaking tables, necessitating substantial equipment and leading to costly and challenging process management. A novel technological concept, such as RC, may be introduced to address these issues by using fluidized bed technology to facilitate gravity separations in both mineral processing and coal washing. Consequently, this method has evident promise for pretreatment the chromite tailings. RC has numerous benefits compared to spiral concentrators and shaking tables, particularly fine tables. The benefits contain comparable or superior separation performance, reliable process, reduced space demands, uniform product quality, and elevated capacity. Moreover, the combination of the teetering bed and the enhanced water distribution system in the RC may provide more efficienct separation.

## References

ALTIN, G., INAL, S., IBRAHIM, ALP, I., 2018. *Recovery of chromite from processing plant tailing by vertical ring and pulsating high-gradient magnetic separation*. MT Bilimsel, 13, 23–35.

AMARIEI, D., MICHAUD, D., PAQUET, G., LINDSAY, M., 2014. *The use of the Reflux Classifier for iron ores: assessment of fine particles recovery at pilot scale*. Miner. Eng. 62, 66–73.

BURT, R. O., MILLS, C., 1984. *Gravity concentration technology.* In Developments in mineral processing, ed. D. W. Fuerstenau, vol. 5, 111–351. London: Elsevier.

DAS, A., SARKAR, B., MEHROTRA, S.P., 2009. *Prediction of separation performance of Floatex Density Separator for processing fine coal particles*. Int. J. Miner. Process., 91(1), 41–49.

DEHGHANI, H., NOZARI, M., 2018. *Application of gravity separators for enrichment of South African chromite tailings*. Journal of Mining and Metallurgy, Section A: Mining, 54(1), 41–50.

DOROODCHI, E., ZHOU, J., FLETCHER, D.F., GALVIN, K.P., 2006. *Particle size classification in a fluidized bed containing parallel inclined plates*. Miner. Eng. 19, 162–171.

GALVIN, K.P., PRATTEN, S.J., NICOL, S.K., 1999. *Dense medium separation using a teetered bed separator*. Miner. Eng., Vol. 12 (9),. 1069–1081

GALVIN, K.P., 2003. *On the phenomena of hindered settling in liquid fluidized beds*. In: Honaker, R.Q., Forest, W.R. (Eds.), Advances in Gravity Separation. SME Inc., Littleton,. 19–38.

GALVIN, K.P., DOROODCHI, E., CALLEN, A.M., LAMBERT, N., PRATTEN, S.J., 2002. *Pilot plant trial of the reflux classifier*. Miner. Eng. 15, 19–25.

GALVIN, K.P., CALLEN, A., ZHOU, J., DOROODCHI, E., 2005. *Performance of the reflux classifier for gravity separation at full scale*. Miner. Eng. 18, 19–24.

GALVIN, K.P., WALTON, K., ZHOU, J., 2009. *How to elutriate particles according to their density*. Chem. Eng. Sci. 64, 2003–2010.

GALVIN, K.P., ZHOU, J., WALTON, K., 2010. *Application of closely spaced inclined channels in gravity separation*. Miner. Eng. 23, 326–338.

GUPTA, A., YAN, D.S., 2006. *Mineral Processing Design and Operation: An Introduction*. Elsevier, Amsterdam.

HARZANAGH, A.A, ERGUN, S. L., GULCAN, E., 2017. *Beneficiation of oxide ores using dense medium cyclones. A simulation study*. Physicochem. Probl. Miner. Process. 53 (1): 379–93.

HYDE, D.A. WILLIAMS, K.P. MORRIS, A.N. YEXLEY, P.M., 1988. *The beneficiation of fine coal using the hydrosizer.* Mine and Quarry, Vol. 17 (3), pp. 50–54.

IZERDEM, D., 2024. *Low-Grade Chromite Beneficiation Through Spiral Concentration: A Review from the Turkish Market Perspective*. Miner. Process. Extr. Metall. Rev., 1–21.

KARI, C. KAPURE, G. RAO, S.M. RAO, N.D., 2006. *Predicting the chromite mineral upgradation in floatex density separator using hindered settling models*. ISIJ International, 46: 966–973.

KHAKMARDAN, S., DOODRAN, R.J., SHIRAZY, A., SHIRAZI, A., MOZAFFARI, E., 2020. *Evaluation of Chromite Recovery from Shaking Table Tailings by Magnetic Separation Method*. Open J. Geol. 10, 1153–1163

MANKOSA, M.J., KOHMUENCH, J.N., EISENMANN, M.D., LUTTRELL, G. H., 1995. *Testing of Hydrofloat separator for coal cleaning application*, Virginia Polytechnic Institute and State University, Blacksburg, Virginia

MOKEONA, T. NHETA, W., 2020. *Beneficiation of South African chromite tailings using magnetic separation*. In Proceedings of the 6th World Congress on Mechanical, Chemical and Material Engineering, Prague, Czech Republic, 16–18 August 2020.

MORITOMI, H., IWASE, T., CHIBA, T., 1982. *A comprehensive interpretation of solid layer inversion in liquid fluidized beds*. Chem. Eng. Sci. 37 (12), 1751–1757.

MURTHY, Y.R., TRIPATHY, S., 2020. *Process optimization of a chrome ore gravity concentration plant for sustainable development*. J. S. Afr. Inst. Min. Met. 120, 26–268.

ÖZYURT, M.; CEBECI, Y.; ERGÜN, S.L., 2023. *Recovery of chromite from concentrator plant tailings*. Sci. Min. J., 62, 17–21

REFLUX™ *Classifier Fine particle technology* 2024, accessed 01 September 2024, < https://www.flsmidth.com/en-gb/products/centrifugation-and-classification/reflux-classifier>.

REMES, A.; TUIKKA, A.; AND KOVIO, H., 2011. *Simulation and pilot experiments on pyrite concentrate separation in a floatex density separator.* Min. Metall. Process., 28: 62–70.

SARKAR B., DAS A., MEHROTRA SP., 2008. *Study of separation features in floatex density separator for cleaning fine coal.* Int. J. Miner. Process., 86, 40–49.

TRIPATHY, S.K., BANERJEE, P.K. SURESH, N., 2015a. *Magnetic separation studies on ferruginous chromite fine to enhance Cr: Fe Ratio*. nt. J. Min. Metall. Mater. 22 (3):217–24.

TRIPATHY, S.K., BHOJA, S.K., KUMAR, C.R.; SURESH, N., 2015b. *A short review on hydraulic classification and its development in mineral industry*. Powder Technol., Vol. 270, pp. 205–220.

WESSELDIJK, Q.I., REUTER, M.A., BRADSHAW, D.J., HARRIS, P. J., 1999. *The flotation behaviour of chromite with respect to the beneficiation of UG2 Ore*. Miner. Eng. 12 (10):1177–84.

WILLS, B.A., FINCH, J.A., 2015. *Wills' Mineral Processing Technology: An Introduction to the Practical Aspects of Ore Treatment and Mineral Recovery*, eighth ed. Butterworth-Heinemann, Oxford.

YOUNG, C.A., LUTTRELL, G. H., 2012. *Separation technologies for minerals, coal, and earth resources*. Colorado: Society for Mining, Metallurgy, and Exploration (SME).

ZHOU, J., WALTON, K., LASKOVSKI, D., DUNCAN, P., GALVIN, K.P., 2006. *Enhanced separation of mineral sands using the Reflux Classifier*. Miner. Eng. 19, 1573– 1579.