Spiral conditions for the recovery of ultra-fine particles

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ABSTRACT

Spiral separators have been widely accepted as one of the most flexible gravity separation devices for several decades. The International Journal of Mineral Processing, 84, pp. 118 – 132 mentioned that spirals are treating material too coarse for flotation and too fine for dense-media separation. Powder Technology V 102, pp 244 – 252, 1999 stated that there exists a genuine need for extending the performance envelope of spirals – whether to treat finer or coarser material than the traditional size ranges. In recent times there has been an upsurge in interest, particularly in the development of newer fine gravity separators.

The experimental test work showed a movement of mass from the outer region towards the centre column of the spiral, i.e., from the fine tailings band towards the concentrate. As recovery on the spiral trough is a function of mass yield and grade, the ultra-fine 7 spiral had a better recovery than the HX5. This makes the UF7 an ideal rougher spiral.

Spiral separators for the recovery of ultra-fine particles have a unique profile, pitch and features to ensure it performs efficiently. The flow on the spiral trough must be controlled to minimise turbulence that will entrain fine particles in the outer section of the trough.

Keywords: Ultra-fine particles, spiral, design, recovery

1. Introduction

1.1 Spirals

Spirals are one of the types of equipment which have been designed and built to effect separation of minerals by gravity. Spiral concentrators are simple low energy consuming devices that separate minerals on the basis of density. Abela (2003) said the controllable factors that affect the separation efficiency of spiral concentrators include feed tonnage, feed percent solids, volumetric flow rate and volumetric loading. Uncontrollable factors that have an influence on spiral performance are mainly feed grade and slimes content in the feed. Slimes are being defined as material present in the spiral feed with particles <45 microns. Spirals have a limitation in the particle size range that can effectively be treated, this is due to the general geometry and design. The most efficient size range is between 45 and 500 microns in heavy mineral sands applications.

1.1.1.Fine particles

Abela (2003) said that the performance of spiral concentrators is heavily affected by the presence of slimes in the rougher feed. The net effect of efficient slimes removal can cause significant recovery losses of the heavy minerals present in the feed. Abela (2003) defines slimes as material present in the spiral feed with particles <45 µm.

Henderson and MacHunter mentioned that the need to recover fine heavy particles from process streams is becoming increasingly necessary in the mineral sands industry as a number of the potential reserves available for future mining contain finer heavy minerals than those being treated currently. The use of spiral separation technology to treat fine material (80% passing 75 µm), has historically been ineffective at this size range. A fine spiral separator may enable a reduction in the amount of material treated through subsequent processing stages by the rejection of fine liberated gangue material after grinding.

1.2 Design parameters

The design parameters of spiral separators can be summarized as the trough dimensions, added features, ancillary equipment, manufacturing methods and construction materials. MacHunter et al. (2003) indicated that the critical dimensional details of spiral separator troughs include:

- Diameter
- Pitch
- Down-trough slope/s
- Cross-trough slope/s
- Number of turns
- Shape of the trough

The spiral pitch governs the downstream slope of the trough at any given location. The pitch must be sufficiently great to prevent beaching, yet not so large as to generate excessive turbulence and secondary circulation which would inhibit separation. The primary factors that will influence the choice of the pitch are the specific gravity of the solids, the particle sizes to be handled, the flow loading on the spiral and the spiral diameter.

The down trough slope of the trough at any particular location determines the slurry velocity that can be sustained at that point. The transverse slope of the trough is governed by the shape of the trough and in combination the two slopes control the centrifugal acceleration that is applied to the slurry as it flows down the trough. The down trough slope (ϴ) is related to the pitch (p) and the radius of motion (r) as expected in equation 1 (Holland-Batt, 1992):

$$p = 2\pi r \tan\theta \quad (1)$$

It was suggested by Holland-Batt (1995) that if a variation in profile is introduced, these features will promote lateral particle motion in the desired directions once the preliminary settling operation has taken place. The shape of the trough has a profound effect on the nature of the fluid flow phenomena generated as the slurry flows down the spiral and hence on the separation performance. For a given pitch, one profile shape will produce excellent separation but poor solid flow while another profile shape may excel at transporting the solids but perform badly in other respects.

1.3 Criteria for size separation

New model spiral separators have now been developed that are specifically designed to treat material finer than 0.1 mm (100 µm), (Richards et al., 2000). This fine mineral spiral separator is typically longer than traditional troughs to allow these very delicate processes to produce an adequate separation. Richard et al. (2000) debated that very fine heavy particles below approximately 75 µm are typically swept up in the highly turbulent outer regions of existing trough designs and are lost to tailings due to their failure to migrate inwards to the central concentrate collection area. For the spiral separators to perform efficient separations outside the traditional operating window, unique conditions need to prevail in the flowing medium, i.e. a laminar flow with low or no turbulence.

The flow rate has a significant effect on the motion of particles both down and across the trough, providing transportation, stratification and separation. Once the flow regime and the water profile are fully developed it remains in a highly stable condition. The separability of minerals by gravity separation relies on a particle's settling rate in a fluid. The terminal velocity of solid spheres settling in a fluid is described by Stokes Law for fine particles in equation 2 (Wills, 2016):

$$V_{\mathrm{T}} = \frac{g\,(\rho_s - \rho_f)\,d^2}{18\mu} \quad (2)$$

For the recovery of heavy minerals finer than 100 µm to the spiral concentrate product, the flow on the spiral trough must be controlled to minimize turbulence that will entrain fine particles in the outer section of the trough. A more laminar flow regime is required to allow the finer mineral particles to settle to the trough surface and migrate to the concentrate collection area.

1.4 Slurry flow in spirals

The main flow component is obviously down the trough of the spiral and it is controlled by the spiral geometry and the amount of feed slurry. The performance envelope of a spiral is effectively defined by the solids and liquid flow rates. The motion of a particle in a fluid is dependent not only on its specific gravity, but also on its size.

The flow velocity and cross-sectional profile depend on the trough geometry, pitch and flow rate of feed material entering the trough. With increasing flow, the depth and velocity at the inner portion of the trough remains relatively unchanged. However, the flow depth and velocity at the outer region increase.

The fluid radial velocities are generated by difference in the friction effects between the upper part of the flow and the portion in contact with the trough surface. The velocities are directed inwards (towards the spiral column) in the lower parts of the flow and outwards in the upper parts of the flow.

1.5 Spiral models

Tucker (1985) developed a model to describe the particle distribution profile across the spiral trough. In this model, the spiral bed is divided into two zones, the section between the central column to a radius R_0 is called the inner zone, which is approximately 40% of the fractional bed width. The section between a radius R_0 to the edge of the trough is called the outer zone.

The probability of a particle with a density ρ laying in the inner zone at a radial position R ($R < R_0$) is described by equation 3 (Tucker, 1985):

$$\left(\frac{R}{R_o}\right)^{\alpha} tanh\left[\left(\frac{\rho-1}{b1}\right)^{P1} R\right] \tag{3}$$

where P_1 is the first model parameter, α and b_1 are scaling factors.

The probability of a particle laying in the outer zone is described by equation 4 (Tucker, 1985):

$$\emptyset = P2exp\left[-\left(\frac{K}{K_o}\right)^2\right]\left(\frac{d}{s}\right)^{(p-1/b2)^{-0.15}} + P3\left(\frac{s}{d}\right)^{(p-1/b3)^{-2}} \tag{4}$$

where S is the particle size, d is the peak size, P_2 and P_3 are empirical parameters, K is the concentrate port number counted from the top of the spiral and K_0 is a scaling factor.

In equation 4, the first term accounts for the fine particles trapped close to the outer radius, which is depending on the distance down the trough. The second term of the equation relates to the proportion of coarse particles whose equilibrium radius lies within the outer radial zone. Therefore, for a given radial position R, the model becomes equation 5:

$$x = \frac{\left(\frac{R}{R_o}\right)^{\alpha} tan\,h\left[\left(\frac{\rho-1}{b1}\right)^{P1} R\right]}{\emptyset + tan\,h\left[\left(\frac{\rho-1}{b1}\right)^{P1} R_o\right]} \tag{5}$$

Where x represents the probability that material just above concentrate port K leaves the flow stream at that port. This model successfully predicted the probability of particles with a diameter d and density ρ certain laying into the inner zone.

1.6 Parameters limiting the recovery of small particles

The major limitation with gravity concentration is the treatment of fines and ultra-fines. In the fine size ranges the fluid and viscous forces become dominant relative to the gravity and this in turn affects the separation efficiency. Izerdem et al. 2018 observed that the recovery of very fine particles

(<53 µm) might only reach 30% maximum. As the particle sizes increased up to 200 µm, in general, the recoveries increased.

The flow of particles in fluids is a subcategory of multi-component, multiphase flows, which covers a wide spectrum of flow conditions and applications. In general, the motion of particles depends (Doheim et al., 2013) on the particle properties (size, density and shape), the operating conditions (slurry density and flow rate) and the spiral design (pitch, trough shape, inclination and number of turns). Particle separation is achieved by the combined action of stratification, film sizing, gravitational and centrifugal forces, which occurs when mineral pulp flows down a helical trough.

2. Methodology

The HX5 spiral was compared to the UF7. The HX5 is traditionally known for treating fine material, however, the UF7 was developed for treating ultra-fine material.

2.1 Sample preparation

A chromite sample was obtained from Limpopo. The sample was screened by an external laboratory to >90% passing 75µm. The spiral feed PSD is shown in Figure 1.

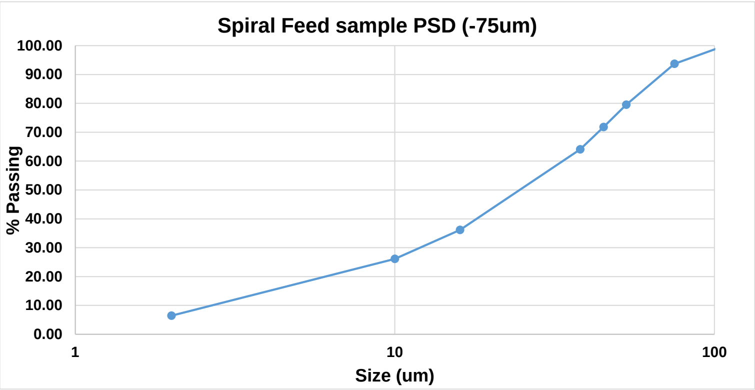

Figure 1: Spiral feed PSD

2.2 Rig setup

The rig and mouth organ are shown in Figure 2. The slurry was fed using a Sala pump to the spiral feed box via a distributor with an overflow to ensure constant feed conditions during the test. The overflow of the distributor is recycled back to the Sala pump.

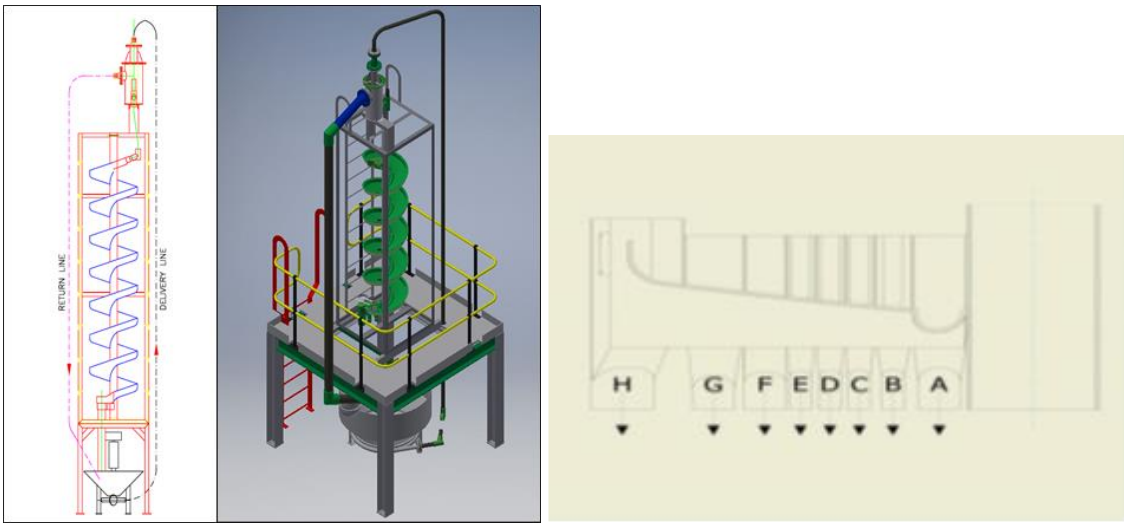

Figure 2: Spiral rig and mouth organ setup

Each spiral stage was run until steady state conditions were reached before taking the relative density (RD) measurements at the top of the spiral rig. Three consistent RD measurements and three consistent flow rate measurements were recorded before taking the simultaneous timed samples (Fraction A to H) from the mouth organ. Mouth organ fraction A represents the sample collected from the inside of the trough. It is the heaviest sample and should contain most of the Cr_2O_3.

The procedure followed a batch procedure, thus re-cycling streams cannot be investigated. In simulations, these recycling streams will be added to give an indication of the mass balance over a single stage process. The simultaneously timed samples were weighed wet and then it was dried and weighed again before sub-dividing. A rotary splitter sampling method was used to produce a representative sub-sample.

2.3 Operational parameters

Table 1 shows the planned versus actual operating parameters. The HX5 and UF7 spirals have different trough angles and pitches.

Table 1

Planned versus actual parameters.

			Planned		Actual	
Spiral	**Trough angle (degrees)**	**Test No:**	**Solids flow rate (t/h)**	**Solids concentration w/w %**	**Solids rate (t/h)**	**Solids concentration w/w %**
HX5	19°	T1	3.6 – 6.0	30 – 50	3.8	39.6
		T2			3.8	39.4
UF7	13°	T1			3.3	39.0
		T2			3.2	38.7

3. Results and discussion

This section presents and discusses results for the gravity concentration of ultra-fine chromite on a novel spiral specifically designed to treat -150µm particles.

3.1 Relationship lines

The grade versus mass yield relationship represents the concentrate grade when a certain percentage of the feed mass on a spiral stage reports to the concentrate. For this application an ideal relationship is a high mass yield percentage containing a high percentage of Cr_2O_3. The recovery versus mass yield relationship illustrates the cumulative recoveries of the materials for each stage at the respective cumulative mass yield. The relationship gives an indication of the amount of material that is recovered at a certain mass yield to the concentrate. A relationship above the 1:1 ratio curve indicates that a recovery of that material has occurred and a relationship below the curve indicates a rejection of that particular material. The further the relationships are away from the 1:1 ratio curve, the more efficiently the material can be separated on the spiral. Figure 4 shows the mass distribution in each mouth organ across the spiral trough. Mass was moved from fraction H to A in the case of the UF7 spiral. As per literature, the spiral with a lower pitch and large diameter, which provides a lower flow speed in the outer region, reduces the amount of valuable minerals lost to the tailings. The size distribution in fraction H was exactly the same on both spirals as per figure 8.

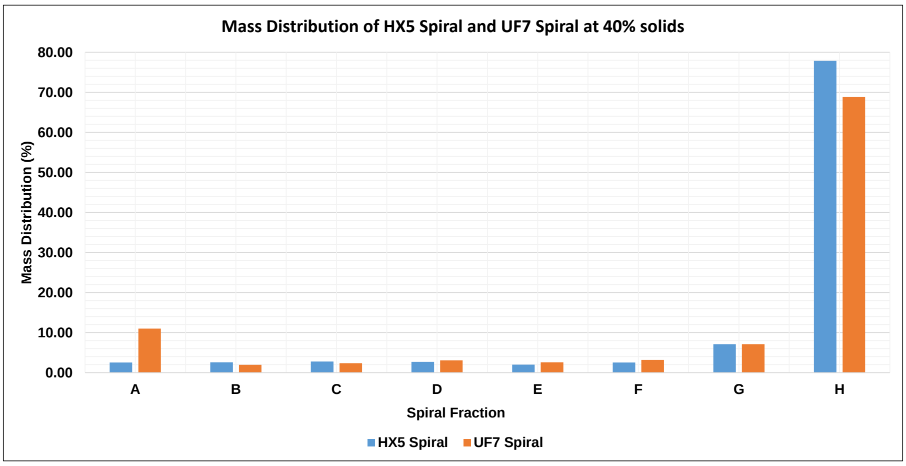

Figure 4: Mass distribution in each mouth organ

Figure 5 shows the UF7 has in general, for the same mass yield, achieved a higher grade than the HX5.

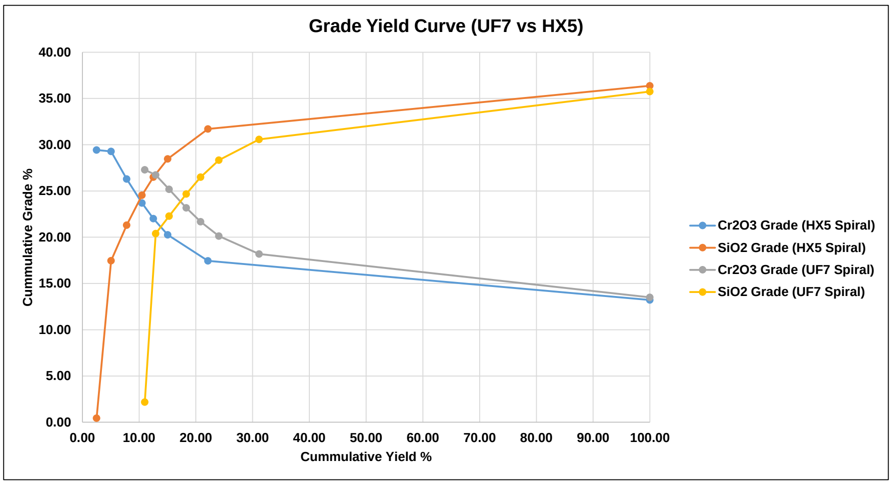

Figure 5: Cumulative grade versus mass yield

Figure 6 shows the UF7 had a better recovery of the Cr_2O_3 than the HX5. This makes the UF7 an ideal rougher spiral. The function of the rougher is to recover the valuable mineral whereas the cleaner afterwards will achieve the required grade.

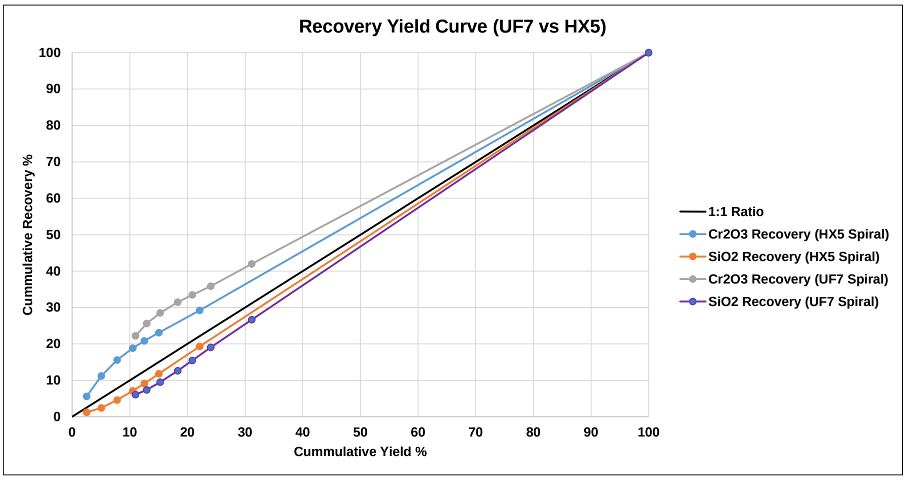

Figure 6: Cumulative recovery versus mass yield.

Recovery is a function of mass yield and grade. As the UF7 had a better mass yield to concentrate, and in general, a better grade for the same mass yield, one would expect a better recovery than the baseline spiral.

Figure 7 shows the better recovery of the Cr_2O_3 to the concentrate in case of the UF7.

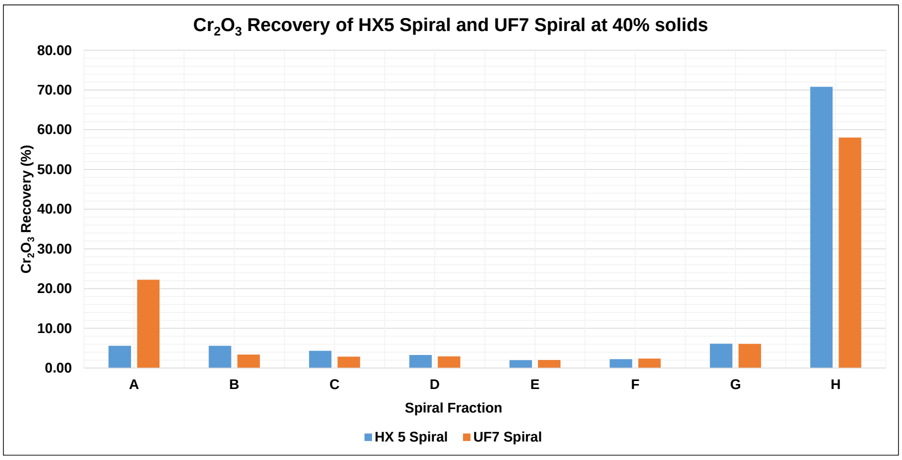

Figure 7: Cr_2O_3 recovery per mouth organ fraction

The particles size in fraction H consists of a valuable material (Cr_2O_3) and coarse silica. Figure 8 shows a movement of mass occurred over the spiral trough, however it does not seem to influence the particle size distribution in the inner and outer fractions.

Figure 8 shows the particle size distribution for fractions A and H.

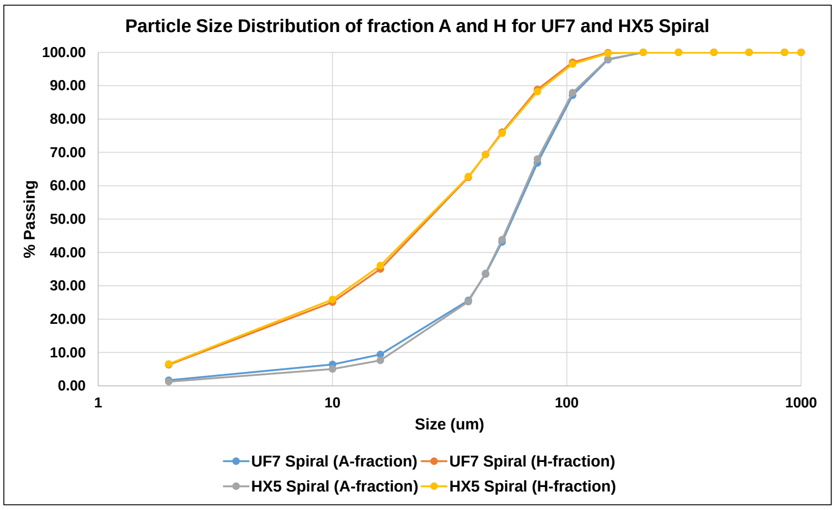

Figure 8: PSD for fraction A and H

Figure 9 shows the spiral separation efficiency as calculated using the Holland-Batt equation, which is:

$$\text{Separation efficiency} = \frac{Recovery - Yield}{100\,\% - feed\ grade} \times 100 \qquad (6)$$

The UF7 spiral had better recoveries and yield to concentrate, which translates to a better separation efficiency.

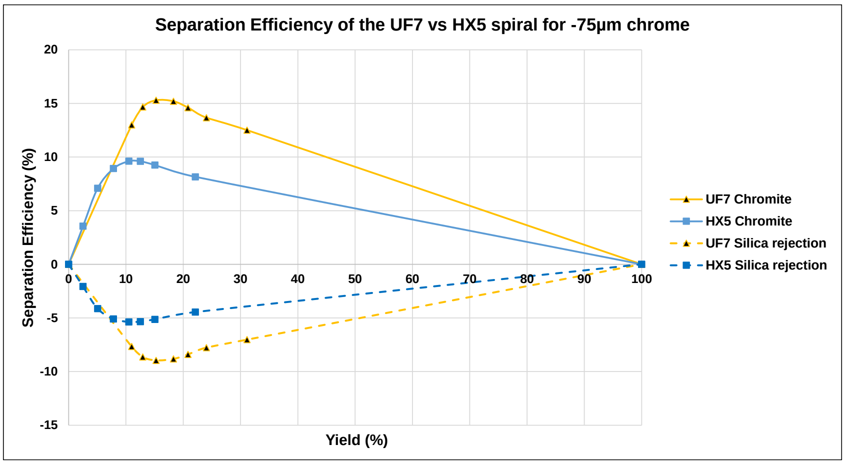

Figure 9: UF7 and HX5 separation efficiency

4. Conclusions

From literature, the spiral pitch governs the downstream slope of the trough. The pitch must be sufficiently great to prevent beaching. It was noted that the UF7 tends to beach with particles in the size range -150 +75 µm. The spiral employed for fine particles normally has a lower pitch (as in the case of he UF7), which can provide a lower flow speed and reduces the amount of valuable mineral lost to tailings. The UF7 has a more laminar flow in the outer regions (as described by Richard et. al., 2000) due to the less steeper downstream slope. This allowed the very fine heavy particles to migrate to the concentrate band (figures 4 and 7). The water profile on the UF7 also shows that the water volume moved from fraction H to G and especially to A. The more laminar flow regime allowed the finer mineral particles to settle to the trough surface and migrate to the concentrate collection area. The particle size distribution of the concentrate and tailings was the same on both spirals. The UF7 spiral had a better separation efficiency in comparison to the HX5.

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