Application of Falcon Centrifuge as a Cleaner Alternative for Complex Tungsten Ore Processing

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Received: 15 June 2019; Accepted: 17 July 2019; Published: 19 July 2019

Abstract: Scheelite (CaWO$_4$) is one of the main raw material for the production of tungsten. It is usually encountered in skarn deposits where it is commonly associated with other calcium minerals as fluorite, apatite, and calcium silicates. Worldwide, scheelite is upgraded to the chemical grades by direct flotation, but the separation efficiency remains limited due to similar flotation behaviors of scheelite and gangue minerals with fatty acid. The only solutions used to overcome this issue involve high energy consumption or ecotoxic reagents. In the present study, a novel method based on the use of a centrifugal Falcon concentrator was investigated to perform an efficient elimination of gangue minerals and fine particles as well as an acceptable scheelite recovery enabling a decrease of the flotation reagents consumption. The performances of the two types of laboratory Falcon bowls, Falcon UltraFine (UF) and Falcon Semi-Batch (SB), were modeled using the design of experiments (DoE) methodology, which allowed to determine the best operating parameters for each bowl. The separation performances were mainly affected by the rotary speed and the pulp density for the Falcon UF and by the rotary speed and the fluidization pressure for the Falcon SB. Due to the fluidization pressure, the Falcon SB exhibited higher gangue minerals rejection with slightly lower recoveries than the Falcon UF. Overall, the optimized Falcon SB test allowed to reach 71.6%, 22.6%, 17.2%, and 12.6% for scheelite, calcium salts, dense calcium silicates, and light non-calcic silicates respectively while the desliming efficiency reached 98.8%. For comparison purposes, a classical hydrocyclone allowed to attain 89.1%, 89.3%, 79.5%, and 76.5% for scheelite, calcium salts, dense calcium silicates, and light non-calcic silicates respectively while the desliming efficiency reached 52.0%. Theses results can be used reliably to assess the separation performances of an industrial Falcon C which can be regarded, along with Falcon SB, as a sustainable and efficient gangue rejection method for complex W skarn ore, which allows the use of environmentally friendly reagents during downstream flotation stages.

Keywords: gravity concentration; Falcon centrifugal concentrator; tungsten-skarn; scheelite; gangue rejection; desliming

1. Introduction

1.1. Challenges in Tungsten Ore Processing

In the global economy, tungsten (W) displays a high economic importance combined with a high supply risk [1–3], which impelled the European Union to classify it as a critical metal [3]. It has few efficient substitutes and still exhibits poor recycling rates due to difficulties in the W recycling processes [1,2]. Hence, primary tungsten extraction still represents the major source of this strategic metal in manufactured products, including alloys, supra-alloys, and tungsten carbide [2]. Scheelite
(CaWO₄) and wolframite ((Fe,Mn)WO₄) are the two main W-bearing minerals exploited for primary tungsten extraction. On the one hand, wolframite usually forms coarse crystals in quartz-veins deposits, which are processed by classical gravity, magnetic, and occasionally froth flotation methods [4,5]. On the other hand, scheelite is mainly encountered in skarn deposits, which account for more than 40% of the global current estimated tungsten reserves [2]. The classification of tungsten as a critical metal resulted in a global resurgence of interest for these ores [5–7]. In such deposits, scheelite is found in fine-grained mineralizations disseminated thorough the orebody and commonly associated with other calcium-bearing minerals such as calcite, dolomite, fluorite, and apatite [5,7–9]. A significant contrast of densities usually exists between scheelite (6.1 g·cm⁻³) and the gangue minerals (2.6–3.4 g·cm⁻³), including the calcium-bearing ones, which is suitable for gravity concentration. However, due to the small liberation size (<150 µm), the classical gravity separation methods are usually inefficient and froth flotation is often preferred to process W skarn ores [7,10,11]. Fatty acids, particularly sodium oleate, are widely used as collectors for scheelite flotation considering their low cost, environmental friendliness, and high efficiency [7,12,13]. However, separation of calcium-bearing minerals by flotation with fatty acids is very difficult due to the tendency of these collectors to chemisorb onto the surface calcium atoms [14–16]. The gangue calcium minerals often contain elements such as P, F, C, and Si that are highly penalizing either for the hydrometallurgy process of the scheelite concentrates or for the final W product [2,17]. Therefore, it is crucial to eliminate these minerals during mineral processing. Though new fatty acids formulations allowed to enhance significantly the separation contrast [12], an acceptable flotation selectivity cannot be attained without either a high energy consumption—e.g., using the Petrov’s process that consists in heating the pulp to 80 °C [18]—or using ecotoxic reagents as lead-benzohydroxamic acid (Pb-BHA) complexes [19,20]. Thus, finding efficient, low cost, and environment friendly processes to beneficiate W-skarn ores is a real challenge for the next decades.

1.2. Enhanced Gravity Concentration Using Centrifugal Separators

Gravity concentration techniques are simple, low costs, and environmental friendly mineral processing techniques since no chemical reagents are needed [21]. Over the past few decades, the necessity of processing more complex ores displaying finer liberation meshes resulted in a decrease of the overall efficiency of classical gravity separation methods [5]. Thus, gravity has been progressively replaced by flotation in processing plants, which demonstrates better performances for the processing of fine-grained ores [5,7]. Nevertheless, flotation also has its limitations, in particular when the minerals which must be separated exhibit similar surface properties, as mentioned before in the case of skarn ores.

Enhanced gravity separators such as Falcon concentrators, which use additional centrifugal force, have been specifically developed to process fine to ultrafine particles, down to 3 µm [22–24]. Falcon concentrators can be used successfully for recycling processes [25,26] as well as for mine tailings reprocessing [27,28] that are key approaches to improve environmental outcomes [29]. Developed in the 1980s by Steve McAlister [30], such separators consist in a bowl capable of spinning at high “G” force, enabling the density separation of fine particles [22,24]. The bowl can be fluidized to avoid compaction and to remove light particles from the concentration zone (Falcon SB), while the Falcon UltraFine (UF) bowl, specifically designed to recover very fine particles, is not fluidized. Rotary speed, pulp density, feed flowrate, and fluidization pressure (for the Falcon SB only) are the main operating parameters involved in the separation [27,28,31–34]. Falcon concentrators are operated in semi-batch mode but, at industrial scale, continuous Falcon concentrators (Falcon C) can process continuously up to 100 t/h of ore with high feed pulp density (up to 45 wt %) [24]. Besides, semi-batch-operated Falcon concentrators (UF and SB) can be used reliably to assess the separation performances of Falcon C and, hence, to demonstrate the viability of the process at industrial scale [35]. Moreover, the Falcon UF as well as the industrial Falcon C do not require wash water, reducing further operating cost and increasing the environment friendliness of this processing method.
Recently, authors demonstrated that Falcon concentrators, as other centrifugal separators, allow
to eliminate efficiently the fine particles (−10 µm), also called slimes [28]. Desliming, which is
recommended for the froth flotation stage since fine particles (−10 µm) are known to disturb the
process, is usually performed using hydrocyclones. These apparatus operate a particle-size-based
separation and do not usually concentrate the dense minerals, even if a pre-concentration of dense
minerals in the underflow is sometimes observed [36]. This work investigates the use of a Falcon
concentrator prior to flotation to perform both a pre-concentration and a desliming stage on a W-skarn
ore. The main objective of this study is to propose an optimized Falcon separation prior to flotation to
reject the penalizing gangue minerals and, as a side objective, to deslime the ore. Such developments
would lead to the reduction of the overall environmental impacts of skarn ore processing by allowing
the use of cleaner reagents—i.e., fatty acids—and by decreasing the tonnage processed by flotation
and, consequently, the reagents consumption.

2. Material and Methods

2.1. Materials

The ore used in this work is a W-skarn from the Tabuaço deposit (Northern Portugal). It is mainly
composed of silicates (85 wt %), mostly calcium-bearing dense silicates (vesuvianite, zoisite, and grossular)
and, to a lesser extent, non-calcic light silicates such as feldspars and quartz [9]. The remaining fraction
(15 wt %) comprises fluorite (11 wt %), apatite (3 wt %), and scheelite (1 wt %) [9]. The global mineralogical
assemblage can be divided into four different mineral groups displaying specific density ranges (Table 1).
Assuming that all minerals contained in each density range behave similarly during the separation, the
separation performances are estimated using one proxy by minerals group.

The light silicates fraction is dominated by K-feldspar [9], which displays a density very similar to
those of other light silicates such as quartz and Na-feldspar (Table 1). Therefore, the potassium oxide
(K₂O) content can be used as a proxy to estimate the separation performances for this group of minerals.
The gangue calcium-bearing salts group contains apatite and fluorite (Table 1), the elimination of
which is crucial to improve the downstream flotation process. These minerals have very close densities
(Table 1) and their elimination can be approximated using the phosphorous oxide (P₂O₅) content in the
sample, apatite being the only P-bearing mineral in the ore [9]. The dense silicates group comprises
pyroxenes, garnets, vesuvianite, and zoisite, which all contain iron and calcium [9]. To assess the
rejection performances for this mineral group, the iron oxide (Fe₂O₃) content can be used as these
minerals are the only Fe-bearing minerals in the Tabuaço ore [9]. Although
most of the clay minerals reported contain potassium and iron, they can be classified as light silicates
since their densities are close to 2.6. Considering the small amounts of phyllosilicates in the ore, their
contribution in terms of iron can be neglected [9].

Table 1. Mineralogical composition of the Tabuaço W-skarn showing the relative abundances along with
the chemical formulas, and the densities of the minerals which are classified into four different groups.

| Mineral             | Formula                        | Abundance (wt %) | Density (g cm⁻³) | Group                |
|---------------------|--------------------------------|-----------------|------------------|----------------------|
| Vesuvianite         | Ca₁₀(Mg,Fe)₂Al₂(SiO₄)₂(Si₂O₇)₂(OH)₄ | 45              | 3.30             | Dense silicates      |
| Epidote (zoisite)   | Ca₂(Al,Fe)₃(SiO₄)₃(OH)          | 15              | 3.20             | Dense silicates      |
| Fluorite            | CaF₂                           | 10              | 3.18             | Calcium salts        |
| Feldspars           | (K,Na)AlSi₃O₈                   | 15              | 2.65             | Light silicates      |
| Phyllosilicates     | -                              | 1-5             | 2.65             | Light silicates      |
| Garnet (grossular)  | Ca₃(Al,Fe)₂(SiO₄)₃              | 1-5             | 3.70             | Dense silicates      |
| Fluorapatite        | Ca₅(PO₄)₃F                     | 3               | 3.18             | Calcium salts        |
| Pyroxene (diopside) | Ca(Fe,Mg)₃Si₂O₆                | 1               | 3.20             | Dense silicates      |
| Quartz              | SiO₂                           | 1               | 2.65             | Light silicates      |
| Scheelite           | CaWO₄                          | 1               | 6.10             | Target mineral       |
The samples were crushed in three successive jaw crushers and a gyratory crushe to produce a ~4 mm fraction. To avoid any over-grinding, the ground material was sieved and only the +150 µm material was then fed to a ball mill to reach the liberation size, estimated between 150 and 200 µm by optical microscopy. As the desliming efficiency of the Falcon has been investigated, the feed, corresponding to the ~150 µm product, was not deslimed prior to the tests. The particle size distribution and WO₃, P₂O₅, K₂O, and Fe₂O₃ distributions in the Falcon feed are presented in Figure 1. Scheelite is mostly distributed in the finest fractions (~100 + 44 µm) with an average grade of 1.0% WO₃. The studied major oxides display similar size distributions which roughly follow the weight distribution, although the dense silicates are more distributed in the fine fractions while the light silicates are more distributed in the coarse fractions (Figure 1).

![Figure 1. WO3 grade, wt % retained and main oxides size-distributions in feed material used for the Falcon tests.](image)

2.2. Chemical Analyzes

Representative aliquots were analyzed by energy dispersive X-ray fluorescence spectroscopy (ED-XRF) using a Niton™ XL3t (Thermo Scientific, Waltham, MA, USA) portable analyzer to measure the W, K, Fe, and P contents and calculate the WO₃, K₂O, Fe₂O₃, and P₂O₅ contents and their recoveries used as proxies in this work. Results were calibrated using standards analyzed by ICP-AES/ICP-MS at the Service d’Analyses des Roches et des Minéraux (SARM-CNRS, Nancy, France).

2.3. Falcon Tests

The Falcon concentrator used in this work was a Falcon L40 laboratory model (Sepro Mineral Systems, Vancouver, BC, Canada). Tests were performed with the two bowl types, i.e., the 4” smooth-walled Falcon UF bowl and the Falcon SB bowl, to compare their efficiency. During the tests, the feed slurry was kept homogeneous and the feed flowrate, called pulp flowrate hereafter, maintained constant (Figure 2). In addition, a by-pass was placed at the output of the feed tank to allow operating in closed circuit during feed preparation, for pulp density adjustment and flowrate control. Feed dry weight was set at 500 g for both Falcon UF and Falcon SB, based on preliminary saturation tests which allowed to set the maximum feed weight to work with to avoid saturation of the bowl [28].
The design of experiments (DOE) methodology allows to study the influence of \( k \) parameters at \( l \) levels for one or several response(s) \([37]\) and to model these responses from the studied parameters. Some design of experiments such as Box–Behnken and Central Composite Design are suitable for parameter optimization by developing second-order models:

\[
y = a_0 + \sum_{i=1}^{k} a_i x_i + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} a_{ij} x_i x_j + \sum_{i=1}^{k-2} \sum_{j=1+i}^{k-1} \sum_{l=j+1}^{k} a_{ijl} x_i x_j x_l + \ldots + a_{ijk} x_i x_j x_k + \sum_{l=1}^{k} a_{il} x_i^2 + \varepsilon \tag{1}
\]

where the \( x_i \) are the measurable variables (factors); \( a_0, a_i, a_{ij}, \ldots, a_{ik} \) are the constant, linear, interaction, and quadratic model coefficients, respectively; and \( \varepsilon \) is a residual. The coefficients and the residual are determined using the least square method on the experimental results \([37, 38]\).

In this paper, the DOE methodology has been used to gain understanding on the influence of the operating parameters on the separation efficiency, for the two types of Falcon bowls (UF and SB), and to optimize the separation in terms of gangue minerals rejection. Hence, Central Composite Designs (CCD) with two centered points were generated using the JMP® statistical software (SAS institute) D-optimal design tool, as per the procedures in \([38]\). Through the design of experiments, the influences of the rotary speed, the pulp flowrate and the solid pulp density, plus the fluidization pressure for the Falcon SB only, were investigated in order to optimize the Falcon separation (Table 2). The levels were defined in accordance with results of preliminary tests and the operating range recommended by the manufacturers. The rotary speed could only vary between 20 and 78 Hz for the Falcon L40, pulp...
density was chosen as low as possible (2% being the lowest realistically possible pulp density), the feed flowrate levels were chosen as low as possible to avoid settling in the feed and as high as possible to avoid the feed to overflow from the Falcon feeder, and the levels for the fluidization pressure where chosen in accordance with the manufacturer guidance with regard to the sample maximum particle size. Since the chosen levels defined a large experimental domain, the axial value of the CCD was set to 1, which induced that each axial point was located on one boundary of the domain.

Table 2. Independent factors and corresponding levels for the experimental designs.

| Factors                          | Symbol | Levels       | Coded Variables |
|----------------------------------|--------|--------------|-----------------|
| Rotary speed (Hz)                | ω      | Low (−1) 30  | x₁ = (ω − 50)/20 |
|                                  |        | Center (0) 50|                 |
|                                  |        | High (+1) 70 |                 |
| Pulp density (wt % solid)        | %s     | 2 6 10       | x₂ = (%s − 6)/4 |
| Pulp flowrate (kg min⁻¹)         | Q      | 1 2 3        | x₃ = (Q − 2)/1 |
| Fluidization pressure (PSI) *    | f      | 1 2 3        | x₄ = (f − 2)/1 |

* Falcon SB only.

The main objective was to use the Falcon concentrator as a pre-concentrating apparatus, to produce a W pre-concentrate from a complex scheelite-containing ore to feed a fatty-acid flotation circuit. An optimized elimination of gangue minerals and fine particles (−10 µm) was required to ensure the selectivity of the subsequent flotation process. Therefore, K₂O, Fe₂O₃, and P₂O₅ recoveries were used as indicators to estimate the rejection of the corresponding gangue mineral groups. The WO₃ recovery characterized the separation performance in terms of target mineral recovery, and was kept as high as possible. Finally, to compare the desliming action of Falcon concentrators to that of a classical hydrocyclone, the ‘desliming efficiency’ (Déff) was defined as the ratio of the amount of −10 µm particles in the tailings over the amount of −10 µm particles in the feed. In total, five performance indexes were considered. Overall, moderate and tight objectives were defined for the Falcon separation indexes—i.e., the five studied responses—that are detailed in Table 3. The tight criterion, if reached, would represent a significant improvement in skarn ore processing since high calcium gangue minerals and fine particles eliminations would increase tremendously the efficiency of the flotation process while reducing reagents consumption.

Table 3. Moderate and tight objectives based on the five studied responses for the Falcon separation performances.

| Response            | Criterion |
|---------------------|-----------|
|                     | Moderate  | Tight    |
| WO₃ recovery        | 70%       | 75%      |
| P₂O₅ recovery       | 40%       | 25%      |
| K₂O recovery        | 40%       | 20%      |
| Fe₂O₃ recovery      | 40%       | 20%      |
| Desliming efficiency| 60%       | 90%      |

3. Results and Discussion

3.1. Falcon UF

3.1.1. Design of Experiments Results

The experimental results, summarized in Table S1 in Supporting Information (SI), were used to determine the second order response models, after the equation (1). These models represent the expression of the studied responses (WO₃ recovery, K₂O recovery, P₂O₅ recovery, Fe₂O₃ recovery, and Déff) as a function of the coddled operating variables. The significance of each developed model
was estimated through an analysis of variance (ANOVA), see Table S2 in SI. A first F-test was conducted on the models, with all the factors and their interactions. The critical F-value for the 0.05 significance level were calculated using the degrees of freedom (DF) of the models (10) and the residuals (5) for the first run, which is $F_{(10,5)} = 4.74$. The significance of each factor was assessed by comparing the calculated F-value for each factor to the critical F-value. For each model, the non-significant factors were eliminated from the models one by one, the coefficients were re-calculated, and the ANOVA was performed again after each elimination. Finally, only the significant factors were included in the final models and the ANOVA was conducted again on the final models to assess their significance. The calculated F-values for each final model, given in Table S2 in SI, are significantly higher than the critical F-values, which are, for a 0.05 significance level, $F_{(3,12)} = 3.49$ for the $R_W$, $R_K$, and $R_{Fe}$ models; $F_{(2,13)} = 3.81$ for the $R_P$ model; and $F_{(1,14)} = 4.60$ for the $D_{eff}$ model, inducing low p-values.

The accuracy of the models was assessed by the relationships between the observed experimental values and the predicted results (Table 4) The correlation coefficient ($R^2$) and the root-mean-square errors (RMSE) were used to illustrate the accuracy and the strength of these relationships (Table 4). The correlation coefficients are quite high for the gangue minerals recoveries ($>0.8$) but significantly lower for the $WO_3$ recovery and the desliming efficiency for which $R^2 = 0.5801$ and $R^2 = 0.5435$, respectively, indicating that the models accuracy is relatively low.

### Table 4. Summary of fit (actual vs. predicted) for the five studied responses for the Falcon UF.

| Model Statistics | $R_W$ | $R_K$ | $R_P$ | $R_{Fe}$ | $D_{eff}$ |
|------------------|-------|-------|-------|----------|----------|
| $R^2$            | 0.5802| 0.9420| 0.8810| 0.9121   | 0.5492   |
| RMSE             | 5.5592| 2.7470| 4.3503| 3.5020   | 5.0488   |
| F                | 5.5300| 64.9100| 48.1000| 41.5300 | 17.0600 |
| P                | 0.0128| <0.0001| <0.0001| <0.0001 | 0.0010   |

#### 3.1.2. Interpretation of the Models

For each model, a Student’s t-test was performed on each coefficient to assess the significance of their impact on the results. The coefficients, their standard errors, and their significance (p-value) are summarized in Table 5. All the non-significant factors have been eliminated to obtain the final models, which induces that all the remaining factors have a p-value below 0.05—i.e., the chosen significance level.

### Table 5. Parameter estimates for the final models for the Falcon UF as a function of the standardized parameters with standard errors (STD), t-ratios (T), and corresponding p-values (P).

| Term               | Estimate | STD Error | T      | P            |
|--------------------|----------|-----------|--------|--------------|
| $R_W$              |          |           |        |              |
| Constant           | 87.52    | 2.27      | 38.56  | <0.0001      |
| $x_1 (\omega)$     | -3.90    | 1.76      | -2.22  | 0.0464       |
| $x_2 (\%_s)$       | 3.89     | 1.76      | 2.21   | 0.0472       |
| $x_1 (\omega \times \omega)$ | -7.47 | 2.87 | -2.60 | 0.0232 |
| $R_K$              |          |           |        |              |
| Constant           | 39.21    | 0.69      | 57.09  | <0.0001      |
| $x_1 (\omega)$     | -5.62    | 0.87      | -6.47  | <0.0001      |
| $x_2 (\%_s)$       | 10.08    | 0.87      | 11.60  | <0.0001      |
| $x_3 (Q)$          | -3.71    | 0.87      | -4.28  | 0.0011       |
| $R_P$              |          |           |        |              |
| Constant           | 49.26    | 1.09      | 45.29  | <0.0001      |
| $x_1 (\omega)$     | -8.08    | 1.38      | -6.08  | <0.0001      |
| $x_2 (\%_s)$       | 10.81    | 1.38      | 7.85   | <0.0001      |
Table 5. Cont.

| Term  | Estimate | STD Error | T     | P         |
|-------|----------|-----------|-------|-----------|
| $R_{Fe}$ Constant | 45.41 | 0.88 | 51.87 | <0.0001  |
| $x_1$ ($\omega$) | -6.58 | 1.11 | -5.94 | <0.0001  |
| $x_2$ ($%$) | 10.06 | 1.11 | 9.08  | <0.0001  |
| $x_3$ (Q) | -2.89 | 1.11 | -2.61 | 0.0230   |

| $D_{eff}$ Constant | 63.65 | 1.26 | 50.42 | <0.0001  |
| $x_2$ ($%$) | -6.59 | 1.60 | -4.13 | 0.0010   |

The final models can be expressed as a function of the coded variables

$$R_W = 87.52 - 3.90x_1 + 3.89x_2 - 7.47x_1^2$$

(2)

$$R_W = 87.52 - 3.90x_1 + 3.89x_2 - 7.47x_1^2$$

(3)

$$R_K = 39.21 - 5.62x_1 + 10.08x_2 - 3.71x_3$$

(4)

$$R_P = 49.26 - 8.08x_1 + 10.81x_2$$

(5)

$$R_{Fe} = 45.41 - 6.58x_1 + 10.06x_2 - 2.89x_3$$

(6)

$$D_{eff} = 63.65 - 6.59x_2$$

(7)

The WO$_3$ recovery depends significantly on the rotary speed (linear and quadratic terms) and on the pulp density. The rotary speed affects negatively the WO$_3$ recovery for the linear and quadratic terms while the pulp density acts positively on this response. The intercept is high (87.52), which indicates a high WO$_3$ recovery at the center of the experimental domain. As the entrapment of a particle is directly linked to its settling length in the bed [33,34,39,40], scheelite settles probably very fast at the considered operating conditions. The gangue minerals recoveries (proportional to K$_2$O, P$_2$O$_5$, and Fe$_2$O$_3$ recoveries) show similar trends: as the WO$_3$ recovery, they are all affected by a significant negative effect of the rotary speed whereas the pulp density displays a high positive coefficient. The increase of the rotary speed results in the application of a higher G-force and then of a higher cut-off density [33,34], which induces a better rejection of light particles as well as, to a lesser extend, dense particles. The effect of the pulp density can be linked to the differential settling, which is the main separation mechanism occurring in the bowl. When the pulp density is too high, forced settling of light particles may occur, attributed to the superposition of particles with different densities in the flowing film [41,42]. It affects the sedimentation length of both light and dense particles inducing that the light ones are trapped while they should not be. Moreover, the flowrate acts negatively on the K$_2$O and Fe$_2$O$_3$ recoveries. This result can be attributed to the presence of phyllosilicates in light silicates and dense silicates groups, since their characteristic shape can result in stronger entrainment phenomenon [41–43]. Moreover, it can also be linked to the erosion mechanisms in the bowl that are undoubtedly stronger for higher pulp flowrates and might affect more significantly the light minerals [28]. Overall, for the gangue mineral recoveries, the pulp density has a higher effect in absolute value than the rotary speed, indicating a strong control of the settling mechanisms on the separation. The coefficients have the same magnitude between the three gangue mineral groups but some differences can be discussed. The constant term, indicating the value of the response at the center of the domain, is the lowest for the light silicates (39.21), the highest for the calcium minerals (49.26), and intermediate for the dense silicates (45.41). However, following Table 1, the dense silicates display higher densities than the calcium minerals and, then, their constant term should be higher. This phenomenon could be attributed to the existence of iron-bearing silicates (biotite, iron-bearing chlorites, iron-bearing clay minerals, etc.) that are lighter than the calcium minerals. Also, the densities
considered for the calcium minerals could be inaccurate, as they have been measured for ideal minerals, from reference tables. The negative coefficient affecting the rotary speed is the lowest for the light silicates (−5.62), the highest for the calcium minerals (−8.08), and intermediate for the dense silicates (−6.58), in absolute values, which is in accordance with the previous discussion. Additionally, the recovery is low at the center of the domain for the light silicates, which results in a low term affecting the rotary speed for the light silicates. The same trend is followed by the other two responses, as the rotary speed is the main parameter influencing the density cut [34].

The desliming efficiency is significantly affected by a negative effect of pulp density. It means that a high pulp density induces the trapping of fine particles in the concentrate bed, which could be attributed to the forced settling occurring for fine particles as well as for light particles. Moreover, it could also be linked to the second separation mechanism occurring in the bowl, namely the erosion of the concentrate bed. Indeed, with 500 g of feed material, once the concentrate bed is formed, erosion phenomenon are likely to occur as described by Dehaine et al. [28]. The same authors showed that the erosion phenomenon is linked to the shear forces induced by the flow of the pulp at the surface of the concentrate bed [28]. Consistently, the shear forces are higher when the pulp density increases due to the interaction between particles and the concentrate bed surface, that are not taken into account in the current physical separation model of the Falcon yet. Also, the suggested model for the lift forces strongly depends on the particle size which results in a higher erosion rate for coarse particles [28]. This phenomenon could explain the lower desliming efficiency when the pulp density is increased. However, regarding the accuracy of the model, the interpretations are difficult.

### 3.1.3. Optimization and Validation

Following the models for the different responses, the iso-response graphs presented in Figure 3 display the gangue minerals recoveries as a function of the operating parameters. No iso-response graph and no performance objective were established for $D_{eff}$ as it is affected by only one parameter. Optimum operating conditions were selected based on the models determined previously, through the iso-responses graphs (Figure 3). The areas attaining the moderate performances objectives are indicated in Figure 3a while the tight objectives are attained only for WO$_3$ recovery. None of the studied responses reach an extremum on the domain. The WO$_3$ recovery is maximum at intermediate rotary speed and high pulp density but satisfies the performances objectives in the whole experimental domain. The K$_2$O recovery is minimum at high rotary speed, high pulp flowrate, and low pulp density (Figure 3b–d). The other gangue mineral recoveries (P$_2$O$_5$ and Fe$_2$O$_3$) are minimum at high rotary speed and low pulp density (Figure 3e–h). Since the WO$_3$ recovery attains the performances objectives on the whole experimental domain, the gangue minerals recoveries can be minimized while the WO$_3$ recovery remains higher than 70% (and matches the moderate performances objectives), which however results in WO$_3$ losses: the similar trends followed by the gangue minerals and scheelite induces that a compromise has to be done between the WO$_3$ recovery and the gangue mineral rejection.

Global iso-responses graphs have been built for the five considered responses as a function of the operating parameters to select the optimum operating conditions taking into account all the responses (Figure 4). Zones corresponding to the operating conditions for which the responses comply with the moderate objective are indicated on the graphs. Thus, the moderate objective can be reached by maximizing the pulp flowrate and the rotary speed (3 kg·min$^{-1}$ and 70 Hz, respectively) while minimizing the pulp density (2 wt % solid).
Figure 3. 2-D contour plots for WO$_3$ recovery (a), K$_2$O recovery (b–d), P$_2$O$_5$ recovery (e), and Fe$_2$O$_3$ recovery (f–h) for the Falcon UF models as a function of the operating parameters. The colored zones correspond to values that satisfy the performance objectives defined in Table 3.

To validate the developed models, a series of tests with the optimized operating conditions was performed. This experience was reproduced 4 times to assess the experimental variability. For each response, the mean and the standard deviation were calculated based on the four reproduced experiences, see Table 6. The experimental standard deviation was also expressed as a percentage of the experimental value. The error between the predicted values and the average obtained values for the studied responses was used to assess the validity of the model. The experimental errors are low, indicating a good reproducibility of the experiments. The errors between the predicted and the observed values are acceptable for most responses (<10%) with the exception of the W recovery.

Table 6. Validation test for the Falcon UF based on a test with optimized parameters ($\omega = 70$ Hz; $%_S = 2$ wt%; $Q = 3$ kg min$^{-1}$) repeated four times.

| Validation Data                             | $R_W$ | $R_K$ | $R_P$ | $R_{Fe}$ | $D_{eff}$ |
|--------------------------------------------|-------|-------|-------|----------|----------|
| Mean                                       | 63.73 | 24.19 | 25.45 | 22.62    | 72.51    |
| Absolute experimental standard deviation | 1.94  | 1.30  | 1.89  | 1.26     | 1.46     |
| Predicted by the model                     | 72.26 | 19.80 | 30.37 | 25.89    | 70.24    |
| Model absolute error                       | 8.53  | -4.39 | 4.92  | 3.27     | -2.27    |
Figure 4. 2-D contour plots for the five studied responses (WO$_3$, K$_2$O, Fe$_2$O$_3$, and P$_2$O$_5$ recoveries and desliming efficiency) for the Falcon UF models as a function of the operating parameters (a): pulp density and rotary speed; (b): pulp flowrate and rotary speed; (c): pulp flowrate and pulp density). Targets represent zones where the objectives set on all the studied responses, defined in Table 3, are reached.

3.2. Falcon SB

3.2.1. Design of Experiments Results

As for the Falcon UF, the experimental results of the Falcon SB tests (Table S3 in SI) were used to define the second order response functions, after the Equation (1). These functions represent the expression of the responses (WO$_3$ recovery, K$_2$O recovery, P$_2$O$_5$ recovery, Fe$_2$O$_3$ recovery, and $D_{eff}$) as a function of the operating parameters. The same methodology than for the Falcon UF was applied here. The critical $F$-value for a 0.05 significance level were calculated using the degrees of freedom (DF) of the models (19) and the residuals (6) for the first run, which is $F_{(19,6)} = 3.88$. The calculated $F$-values for each final model, given in Table S4 in SI, are significantly higher than the critical $F$-values, which are, for a 0.05 significance level, $F_{(5,20)} = 2.71$ for the $R_W$ model and $F_{(2,23)} = 3.42$ for the $R_K$, $R_P$, and $R_{Fe}$ models, and $F_{(3,22)} = 3.05$, inducing low $p$-values (Table S4 in SI).
The models accuracies were estimated by the relationships between the observed experimental results and the predicted values. The correlation coefficient ($R^2$) and the root-mean-square errors (RMSE) were used to illustrate the accuracy and the strength of these relationships, see Table 7. The correlation coefficients are very similar for all the minerals recoveries and for the desliming efficiency, around 0.7, which is acceptable.

**Table 7.** Summary of fit (actual vs. predicted) for the five studied responses for the Falcon SB.

| Model Statistics | $R_W$ | $R_K$ | $R_P$ | $R_{Fe}$ | $D_{eff}$ |
|------------------|-------|-------|-------|----------|----------|
| $R^2$            | 0.6989| 0.6523| 0.6904| 0.7125   | 0.6921   |
| RMSE             | 6.2631| 3.3917| 3.4524| 2.9182   | 2.6222   |
| $F$              | 364.1500| 21.5800| 25.6500| 28.5000  | 16.4900  |
| $P$              | 0.0001| <0.0001| <0.0001| <0.0001  | <0.0001  |

### 3.2.2. Interpretation of the Models

A Student's t-test was performed on each coefficient of each model to assess the significance of their impact on the results. The coefficients, their standard errors, and their significance (t-test) are summarized in Table 8. All the non-significant factors have been eliminated to obtain the final models, which induces that all the presented values have a $p$-value below 0.05.

**Table 8.** Parameter estimates for the final models for the Falcon SB as a function of the standardized parameters with standard errors (STD), t-ratios ($T$), and corresponding $p$-values ($P$).

| Term       | Estimate | STD error | $T$   | $P$   |
|------------|----------|-----------|-------|-------|
| $R_W$      |          |           |       |       |
| Constant   | 77.33    | 2.21      | 34.92 | <0.0001|
| $x_1 (\omega)$ | 6.56    | 1.48      | 4.45  | 0.0002 |
| $x_2 (\%)$ | -3.25    | 1.48      | -2.20 | 0.0398 |
| $x_4 (f)$  | -3.52    | 1.48      | -2.39 | 0.0270 |
| $x_1 \ast x_4 (\omega \ast f)$ | 4.37    | 1.57      | 2.79  | 0.0113 |
| $x_4^2 (f \ast f)$ | -7.69  | 2.66      | -2.89 | 0.0091 |
| $R_K$      |          |           |       |       |
| Constant   | 14.59    | 0.67      | 21.94 | <0.0001|
| $x_1 (\omega)$ | 3.82    | 0.80      | 4.77  | <0.0001|
| $x_4 (f)$  | -3.61    | 0.80      | -4.51 | 0.0002 |
| $R_P$      |          |           |       |       |
| Constant   | 24.58    | 0.68      | 36.30 | <0.0001|
| $x_1 (\omega)$ | 3.87    | 0.81      | 4.75  | <0.0001|
| $x_4 (f)$  | -4.36    | 0.81      | -5.36 | <0.0001|
| $R_{Fe}$   |          |           |       |       |
| Constant   | 20.19    | 0.57      | 35.28 | <0.0001|
| $x_1 (\omega)$ | 3.82    | 0.69      | 5.56  | <0.0001|
| $x_4 (f)$  | -3.52    | 0.69      | -5.11 | <0.0001|
| $D_{eff}$  |          |           |       |       |
| Constant   | 97.16    | 0.93      | 104.81| <0.0001|
| $x_1 (\omega)$ | -2.94   | 0.62      | -4.75 | <0.0001|
| $x_4 (f)$  | 2.02     | 0.62      | 3.26  | 0.0036 |
| $x_1^2 (\omega \ast \omega)$ | -4.49   | 1.11      | -4.03 | 0.0006 |
The final models are expressed as a function of the coded variables.

\[
R_W = 77.33 + 6.57x_1 - 3.25x_2 - 3.52x_4 + 4.37x_1x_4 - 7.69x_4^2
\]  
(8)

\[
R_K = 14.59 + 3.82x_1 - 3.61x_4
\]  
(9)

\[
R_p = 24.58 + 3.87x_1 - 4.36x_4
\]  
(10)

\[
R_{Fe} = 20.19 + 3.82x_1 - 3.52x_4
\]  
(11)

\[
D_{eff} = 97.16 - 2.94x_1 + 2.02x_4 - 4.49x_4^2
\]  
(12)

The WO\(_3\) recovery depends on the rotary speed, the pulp density, the fluidization pressure (linear and quadratic), and the interaction between the speed and the fluidization pressure. All the coefficients have close absolute values. However, they are negative for the pulp density and for the fluidization pressure (linear and quadratic) but positive for the two other parameters. It induces that the pulp density and the fluidization pressure have a negative effect on the WO\(_3\) recovery. In the Falcon SB bowl, the separation depends mainly on two mechanisms: the differential settling in the flowing film \cite{28,33,34,40,44} and the reorganization of the trapped particles in the gutters \cite{45,46}. It can be assumed that, before reaching the gutters, the particles are subject to a differential settling that can be described by the same physical model than for the Falcon UF bowl despite different bowl geometries. Consistently, the rotary speed increases the scheelite recovery as the settling length of scheelite particles is decreased when the G-force is increased. Moreover, a hindered settling phenomenon appears at high pulp density \cite{41,42} resulting in a decrease of the scheelite recovery and then a negative coefficient for the pulp density. The negative coefficient for the fluidization pressure can be attributed to a low selective particles rejection when the fluidization pressure increases, inducing scheelite losses.

The gangue minerals recoveries follow the same trends, due to their similar densities which are also very similar to the scheelite behavior. The rotary speed acts positively while the fluidization pressure acts negatively, roughly with the same absolute values. A high rotary speed induces a non-selective entrapment as it decreases the settling lengths of all the minerals. In the trapping gutters, the fluidization pressure has an opposite direction compared to the gravity force. Hence, the entrapment of a particle in the gutters depends on the force balance between the gravity force, which is a function of the density and the size of the particle, and drag the force induced by the fluidization pressure. This latter, which has been intensively described for Knelson concentrators, is mainly proportional to the particle area \cite{47–50}. Then, this balance results in a rejection of light particles from the gutters, inducing the negative coefficient for the fluidization pressure on the gangue mineral recoveries. Consistently, the scheelite and the gangue minerals follow very similar trends considering the rotary speed and the fluidization pressure. The absolute values of the coefficients are still different, which can be attributed to their density contrast. It indicates that the scheelite particles are subject to the same force balance and that reaching a better rejection of gangue mineral particles will lead to higher scheelite losses. Overall, the constant terms, as well as the absolute values of the coefficients affecting each operating parameter, can be related with the actual densities of each minerals group.

The desliming efficiency is negatively impacted by the rotary speed (linear and quadratic terms) and positively affected by the fluidization pressure, in the same order of magnitude. The increase of rotary speed leads to the entrapment of fine particles as their settling length is decreased while the fluidization pressure flushes them out from the gutters. The high constant term means that most of the fine particles are rejected with no dependence on the operating parameters in the considered experimental area. The force balance between the gravity force and the fluidization force significantly disfavours the entrapment of fine particles. Indeed, the weight force, responsible for the entrapment of the particle, is correlated to the particle volume and, hence, depends on \(d^3\), where \(d\) is the particle diameter. The pressure force is mainly related to the particle area that is in contact with the water counter-pressure and should be proportional to the particle surface, whose dependence on the particle size is only at a power of 2 \cite{47–50}.
3.2.3. Optimization and Validation

The Falcon SB design yielded more complex models, since, following the equations and the iso-responses graphs (Figure 5), the recoveries of the different minerals, including scheelite, are affected very similarly by the operating parameters. A little loss of recovery is acceptable as the industrial Falcon concentrators are known to be much more efficient than the laboratory-scale Falcon concentrators in terms of recoveries [21,23]. The graphs in Figure 5 present zones corresponding to optimum operating conditions that satisfy the moderate and tight objectives presented in Table 3.

Figure 5. 2-D contour plots for WO$_3$ recovery (a–c), K$_2$O recovery (d), P$_2$O$_5$ recovery (e), Fe$_2$O$_3$ recovery (f), and desliming efficiency (g) for the Falcon SB models as a function of the operating parameters. The green and the red zones correspond to values which satisfy respectively the moderate and the tight performance objectives defined in Table 3.

Optimum operating conditions were selected based on the models determined previously and on Figure 6. A compromise had to be made between the WO$_3$ recovery and the WO$_3$ grade. The global objective was to eliminate the gangue minerals that are problematic for flotation, meaning that the gangue minerals recoveries had to be minimized as much as possible. Hence, following the iso-responses graphs (Figure 6), the pulp density should be minimized (2 wt % solid), the fluidization pressure should be maximized (3 PSI) whereas intermediate rotary speed must be defined (58 Hz) to reach a compromise between WO$_3$ recovery, gangue minerals recoveries, and desliming.

As for the Falcon UF, a test with the optimized operating parameters was performed and reproduced seven times to assess the experimental variability (Table 9). The experimental errors are quite low, indicating a good reproducibility of the experiments. The errors between the predicted and the observed values are very low, indicating a good accuracy of the five developed models.
Figure 6. 2-D contour plots for the five studied responses (WO$_3$, K$_2$O, Fe$_2$O$_3$, and P$_2$O$_5$ recoveries and desliming efficiency) for the Falcon SB models as a function of the operating parameters (a): pulp density and rotary speed; (b): fluidization pressure and rotary speed; (c): fluidization pressure and pulp density). Targets represent zones where the objectives set on all the studied responses, defined in Table 3, are reached.

Table 9. Validation test for the Falcon SB based on a test with optimized parameters ($\omega = 58$ Hz; $\%S = 2$ wt %; $Q = 3$ kg min$^{-1}$; $f = 3$ PSI) repeated seven times.

| Validation Data                   | $R_W$ | $R_K$ | $R_P$ | $R_{Fe}$ | $D_{eff}$ |
|-----------------------------------|-------|-------|-------|----------|----------|
| Mean                              | 71.61 | 12.63 | 22.62 | 17.15    | 98.78    |
| Absolute experimental standard deviation | 3.52  | 1.29  | 3.16  | 1.24     | 0.06     |
| Predicted by the model            | 73.74 | 12.51 | 21.77 | 18.20    | 97.29    |
| Model absolute error              | 2.07  | -0.12 | -0.85 | 1.05     | -1.49    |

3.3. Discussion on Experimental Results

Based on Figure 4, the Falcon UF does not allow to reach the tight objectives defined in Table 3 while the Figure 6 shows that they are reached for very specific operating conditions with the Falcon SB. It demonstrates a higher ability of Falcon SB for the gangue minerals elimination compared to Falcon UF. Further comparisons of the two bowls in terms of gangue minerals elimination and desliming efficiency are presented in Figure 7, using previous results from the DOE. First, the grade-recovery graph for WO$_3$ (Figure 7a) shows that Falcon SB allows obtaining WO$_3$ recoveries ranging from 50% to 86% with WO$_3$ enrichment ratios ranging from 1.83 to 7.92. Due to its optimized bowl design and the addition of a fluidization pressure, the Falcon SB displays better performances than the Falcon UF despite a slight decrease in WO$_3$ recoveries (Figure 7a). This latter produces concentrates with WO$_3$ recovery ranging from 60% to 92% and WO$_3$ enrichment ratio ranging from 1.30 to 2.88 (Figure 7a). As a comparison, the underflow of a classical hydrocyclone stage with a 10 $\mu$m cut-off displays a
1.2 WO$_3$ enrichment ratio for 89% WO$_3$ recovery (Figure 7a). These losses are in accordance with the homogeneous distribution of scheelite in the size fractions.

**Figure 7.** Comparison between a Falcon UF, a Falcon SB, and a classical hydrocyclone in terms of separation performances using DoE results. (a) WO$_3$ recovery versus WO$_3$ enrichment ratio (grade-recovery curve); (b) WO$_3$ recovery versus desliming efficiency; (c) WO$_3$ enrichment ratio versus yield; (d) WO$_3$ recovery versus yield (selectivity curve); (e) WO$_3$ recovery versus gangue minerals recovery.
The desliming efficiency of each apparatus is also presented as a function of the WO$_3$ recovery (Figure 7b). Desliming is very efficient with Falcon SB as the desliming efficiency ranges from 80 to 98%, far better than those obtained with a hydrocyclone (Figure 7b). Indeed, the desliming efficiency with hydrocyclone is 48%, which is around the values obtained with the Falcon UF (Figure 7b). The high desliming performances obtained with both bowls suggest that Falcon concentrators can be used as a pre-concentrating and a desliming apparatus, prior to fatty-acid flotation, therefore substituting to hydrocyclones in flotation feed preparation circuits.

The WO$_3$ enrichment ratio is expressed as a function of the yield in Figure 7c. The yields are comprised between 8% and 33% for the Falcon SB and between 29% and 63% for the Falcon UF. Such values are very well correlated with the WO$_3$ enrichment ratio, as the Figure 7c shows: the highest WO$_3$ enrichment ratios correspond to the lowest yields. Hence, a pre-concentration stage with a Falcon concentrator, in particular the Falcon SB, would lead to a significant decrease of the pulp subjected to the flotation stage, reducing the energy, water, and reagents consumptions. The selectivity curve shown in Figure 7d expresses the WO$_3$ recovery as a function of yield. While the hydrocyclone displays a very poor selectivity, as expected, the Falcon SB is more selective than the Falcon UF, exhibiting lower yields for roughly equivalent WO$_3$ recoveries (Figure 7d).

Another selectivity curve, displaying the WO$_3$ recovery as a function of the gangue minerals recoveries is shown in Figure 7e. Overall, for the best tests in terms of gangue minerals elimination, 89% of the apatite, 89% of the fluorite, and 93% of the silicates (light + dense) are rejected from the concentrate. This crucial result indicates that apatite and fluorite, which are highly problematic in fatty-acid flotation [12,16], can be eliminated by a Falcon pre-concentrating stage prior to flotation.

The rotary speed has a negative effect on the gangue mineral recoveries for the Falcon UF but a positive effect for the Falcon SB. Moreover, the pulp density has very little effect on the recoveries for the Falcon SB and a significant positive effect on the gangue mineral recoveries for the Falcon UF. This may indicate a difference in the separation mechanisms between the two bowls. In the Falcon UF, the separation is mostly governed by the differential settling of the particles in the flowing film, before the concentration zone in the upper part of the bowl. It means that the parameters affect the separation performance by influencing the differential settling mechanisms: the rotary speed decreases the settling length of the particles while the pulp density impels either a hindered or a forced settling of particles. In the Falcon SB, the separation seems mostly lead by the forces balance between the centrifugal force, increasing with the rotary speed and the fluidization pressure. The differential settling occurring in the flowing film before the particles reach the gutters seems to have little influence on the separation performance, indicating that the actual separation happens in the gutters.

4. Conclusions

Gravity concentration of a complex W-skarn has been investigated using a Falcon concentrator with the global aim of eliminating the calcium-bearing minerals that are known to be problematic during fatty-acid flotation. Furthermore, the desliming efficiency was also studied to enable the utilization of the Falcon concentrator as a pre-concentrating and desliming apparatus, prior to flotation. Thus, the influence of the operating parameters on the Falcon UF and Falcon SB performances were modeled using the DOE methodology. It allowed to set the best conditions to attain the elimination of 75% and 78% of the total amount of apatite and fluorite with the Falcon UF and Falcon SB, respectively. The Falcon SB exhibited better performances with up to 98% of fine particles rejected from the pre-concentrate, a WO$_3$ recovery higher than 70%, a WO$_3$ enrichment ratio higher than 4.5, and a yield of around 15%. Given the good elimination of calcium-bearing minerals and fine particles, the pre-concentrate could directly undergo a flotation process with fatty acids as the lack of selectivity between the calcium-bearing minerals would not be a problem anymore. Also, it allowed to reject 85% of the global yield by the physical pre-concentration, leading to a 7-fold of the reagents consumed in the flotation stage, as well as reducing the energy consumption. Since the choice was made to maximize the gangue minerals rejection, the Falcon separation induced around 30% of WO$_3$ losses in the tailings.
compared to around 10% of WO3 losses for a classical hydrocyclone stage. A scavenger Falcon stage could be suggested to reduce these losses, which would anyhow be significantly decreased by up-scaling the laboratory scale Falcon UF and SB to an industrial Falcon C. Indeed, Falcon UF and SB, used at laboratory scale in this study, are operated in semi-batch and thus are not commonly used at industrial scale in continuous operations since they need to be installed in parallel circuits. For this reason, the Falcon C is more widely used in the industry, operating high pulp flowrates that are, unfortunately, not suitable for laboratory test work. However, according to Sepro Mineral Systems [35], the Falcon C efficiency at industrial scale can be assessed based on laboratory tests performed with semi-batch-operated Falcon SB/UF. Overall, replacing hydrocyclones by Falcon concentrators (SB or C) in flotation feed preparation circuits could lead to higher process performances while reducing the environmental impacts by allowing the replacement of usual ecotoxic reagents by the environmentally friendly fatty acids, reducing the reagent and energy consumptions.

**Supplementary Materials:** The following are available online at [http://www.mdpi.com/2075-163X/9/7/448/s1](http://www.mdpi.com/2075-163X/9/7/448/s1), Table S1. Three-variable CCD used for the Falcon UF tests and experimental results, i.e., yield, WO3 (RIW), K2O (Rk2), P2O5 (RP), and Fe2O3 (RFe) recoveries, and Deff; Table S2. Analysis of variance (ANOVA) for the WO3, K2O, P2O5, and Fe2O3 recoveries and the desliming efficiency for the Falcon UF presenting the degrees of freedom (DF), sum of squares (SS), F-ratios (F) and p-values (P) for the first and the final runs. Critical F-values for 0.05 significance level are F(1,5) = 4.74, F(12,2) = 3.49 for the RIW, Rk2, RP models, and F(1,143) = 4.60 for the Deff model; Table S3. Four-variable CCD used for the Falcon SB tests and experimental results, i.e., WO3 (RIW), K2O (Rk2), P2O5 (RP), and Fe2O3 (RFe) recoveries, and Deff; Table S4. Analysis of variance (ANOVA) for the WO3, K2O, P2O5, and Fe2O3 recoveries and the desliming efficiency for the Falcon SB presenting the degrees of freedom (DF), sum of squares (SS), F-ratios (F) and p-values (P). Critical F-values for 0.05 significance level are F(19,6) = 3.88, F(5,20) = 2.71, F(2,23) = 3.42, and F(3,22) = 3.05.

**Author Contributions:** Conceptualization, Q.D., Y.F., I.V.F., and L.O.F.; methodology, Y.F. and Q.D.; software, Y.F. and Q.D.; validation, Q.D., Y.F., I.V.F., and L.O.F.; formal analysis, Y.F. and Q.D.; investigation, Y.F. and Q.D.; resources, L.O.F. and I.V.F.; data curation, Y.F.; writing—original draft preparation, Y.F., Q.D., and L.O.F.; writing—review and editing, Y.F., Q.D., and L.O.F.; visualization, Y.F., Q.D., and L.O.F.; supervision, L.O.F.; project administration, L.O.F. and I.V.F.; funding acquisition, L.O.F.

**Funding:** The research leading to these results has received funding from the European Union’s Horizon 2020 research and innovation program for the FAME project (grant no. 641650). We also acknowledge the support of Labex Ressources 21 supported by the French National Research Agency through the national program “Investissements d’Avenir” (reference ANR–10–LABX–21–01).

**Acknowledgments:** The authors want to acknowledge the technical staff of the experimental station STEVAL, University of Lorraine, Nancy, France, who has been strongly involved in the present work.

**Conflicts of Interest:** The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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