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Modelling heavy and gangue mineral size recovery curves using the spiral concentration of heavy minerals from kaolin residues

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ABSTRACT

Spiral concentrators are one of the most common gravity processing methods extensively used for the concentration of mineral based on their density, particle size and shape. As for every gravity concentration technique, particle size plays a major role in the separation mechanisms within the spiral. Thus, in addition to classical performance indices, such as grade or recovery, partition curves are also a valuable criterion for quantifying the separation efficiency. In this paper, we study and model the influence of wash water additions and pulp density on heavy and gangue mineral partition curves using kaolin residue enriched in heavy minerals and via a design of experiment (DOE). The results show that coarse particle size recovery curves are affected by a systematic decrease, which is mainly impacted by wash water additions. Partition curve modelling through particle size distribution and DOE regression model fitting allow a better understanding of the effect of wash water on the aforementioned phenomenon for each mineral fraction. Gangue minerals are more affected by this phenomenon, which has been interpreted as a result of the Bagnold effect and secondary flows within the spiral. A decrease in the coarse particle recovery represents a significant source of losses, and a better understanding of this phenomenon is necessary to avoid these losses.

1. Introduction

Rare earths elements (REEs) have garnered considerable interest in recent years due to their high economic importance, which is linked to high efficiency electronics and energy technologies. Concerns regarding their supply risk place them on the European Union's list of critical raw materials (EU) [1]. REE recovery from secondary resources, such as industrial process residues, which often display low REE grades but are extremely abundant, provides an alternative to traditional sources [2].

The gravity concentration of primary REE ores is an important initial step in the REE concentration process. It is comprised of a high-capacity gravity separation, taking advantage of the relative high specific gravities (SG) of REE-bearing minerals [3]. Spiral concentrators are high-capacity, low-cost units used for heavy mineral ore concentrations or coal cleaning [4]. It can be illustrated as an inclined chute, which follows a downward helix that is wrapped around a column. It can encompass a variable degree of cross section complexity depending on the model [5]. The principle of separation is based on flowing film stratification in the vertical plane and centrifugal forces in the horizontal plane, as well as other hydrodynamic and friction forces [6]. These forces jointly separate heavy minerals from gangue minerals based on their specific gravity differences. However, spiral separation efficiency is also impacted by the sizes and shapes of the treated particles. Separation mechanisms are also affected by the complex Bagnold force, which is more sensitive to particle size than weight [7–9].

Despite the critical importance of particle size, most of published spiral studies focus on global recovery and few have investigated the recovery according to size-fraction [8,10,11]. The size recovery curve (or partition curve) is a well-known tool used to analyse mineral processing equipment separation based on particles size. Recent iron ore processing studies have shown that heavy and gangue mineral partition curves can separately provide critical information related to spiral separation efficiency [12,13]. However, these studies used chemical contents to determine the behaviour of heavy and gangue minerals. This may cause accuracy issues if significant middling particles are present in the treated material.

The main operating parameters of a spiral separator, in addition to geometric parameters, are feed rate, feed solid pulp density, splitter positions and wash water flowrate. The effects of these parameters on the spiral efficiency have been extensively described in the literature [7,8,14]. Many articles have explored the use of design of experiments (DOE) methodology to model the impacts of these parameters on spiral performance [15–17]. However, few studies have combined this approach with a size recovery analysis based on different minerals in the treated material [12].

This study investigates the influence of wash water flowrate and feed pulp density on the size recovery curves of heavy and gangue minerals in a spiral concentrate using DOE methodology. In addition, a

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method is proposed to model heavy and gangue mineral size recovery curves and assesses the best operating parameters for the spiral concentrator.

2. Materials and methods

Spiral testing was conducted at the STEVAL pilot plant at the GeoRessources laboratory in Nancy, France. This study is based on spiral experiments with a focus on understanding the separation mechanisms within spiral concentrators.

2.1. Materials

The feed material used in this study corresponds to a micaceous residue from a kaolin processing plant. This residue is seen as a potential source of LREE (La, Ce and Nd) and Sn, which is linked to kaolin production [19]. Fig. 1 shows a typical particle size distribution of the raw micaceous residue and for 3 specific gravity fractions, i.e. heavy (SG > 2.89), middlings (2.79 < SG < 2.89) and gangue (SG < 2.79) minerals. Most of the heavy minerals are distributed in the fine fractions, especially in the 53–180 μm range. This size fraction of the micaceous residue, obtained after removing the +180 μm (~25 wt.%) and −53 μm (~18 wt.%) fractions by screening of the raw material, constitutes the feed material of this study.

The main LREE host mineral is monazite (SG = 5.15), while the major Sn host is cassiterite (SG = 6.90). The main gangue minerals are quartz, feldspar and micas, with relatively low specific gravities (SG = 2.6–3). Significant amounts of accessory minerals are also present, including tourmaline (SG = 3.12), topaz (SG = 3.55) and Nb-rutile (SG = 4.25), see Table 1. These accessory minerals have a medium SG, which is much higher than gangue minerals. Thus, they are often recovered in gravity concentrate and are considered heavy minerals in this study. In this study light-gangue and heavy minerals fractions are obtained by dense medium separation combined with centrifugation using bromoform (SG = 2.89). The sample tube bases containing the heavy fractions were frozen using liquid nitrogen to avoid contamination between the heavy and light particles during the recovery of each fraction. Mineralogical observations and X-ray diffraction show that the resulting heavy mineral fraction mostly contains tourmaline, micas, topaz, rutile and all of the metal-bearing minerals, whereas the light fraction only contained gangue minerals, such as quartz, feldspar or micas and some remaining kaolinite.

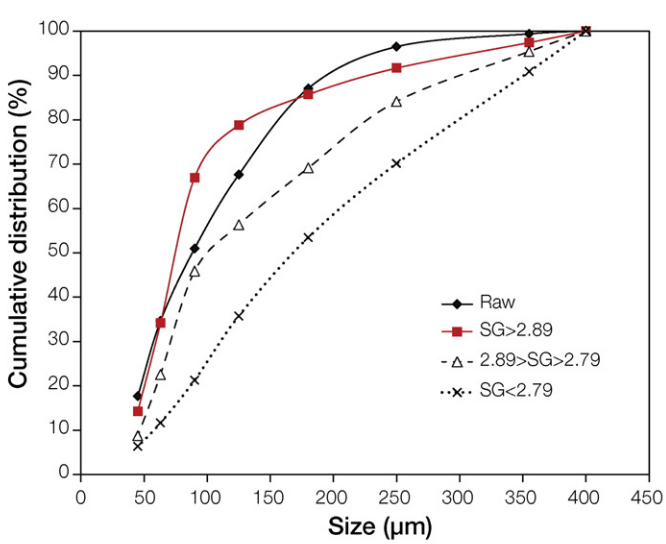

Fig. 1. Typical particle size distribution of the raw micaceous residue and 3 specific gravity fractions.

Table 1
Mineralogical composition of the raw micaceous residue along with specific gravity data.

Mineral	Weight %	Mean SG
Kaolinite	10.15	2.60
Feldspar	15.16	2.60
Quartz	29.79	2.62
Muscovite	14.81	2.82
Chlorite	1.13	2.95
Biotite	14.58	3.00
Tourmaline	9.90	3.12
Apatite	0.86	3.19
Topaz	1.50	3.55
Rutile	0.82	4.25
Zircon	0.64	4.65
Monazite (Ce, La, Nd)	0.07	5.15
Fe oxides	0.52	5.20
Cassiterite	0.08	6.90
Wolframite	<0.01	7.30

2.2. Spiral set-up

The spiral separator used in this paper is a 5 turn MKIIA Reichert spiral (Mineral Deposit Limited, Australia), with a 387 mm pitch, 2370 mm overall height and a 590 mm trough diameter. The dry sample is mixed with water in the mixing tank, forming pulp. The pulp is then pumped to the feed tank (Fig. 2). All spiral outputs discharge into the mixing tank via flexible pipes, which allow sample collection while operating in a closed-circuit. Due to wash water (WW) additions, the feed (F) pulp density decreases during the operation. This dilution can be controlled because the initial pulp density and wash water flowrates are known. Hence, samples can be collected at specific times during the operation to represent a given feed pulp density. The steady state is achieved when sampling is carried out. Because this stage is a roughing stage, the two middling offtakes were considered a single group. Wash water is supplied at each spiral turn via a washwater trough wrapped around the central column. The amount of wash water supplied to each wash water point on the spiral turns was adjusted by rotating the end of the wash water quill inserted in the polyurethane trough to ensure an even distribution of wash water to each turn. The concentrate splitter (cutters) positions were set at the beginning of the tests at a ¾ aperture and remained fixed during the entire experiment.

2.3. Particle size analysis and modelling

Each fraction (float and sinks) was separately analysed using laser light scattering, which assessed the particle size distributions. The particle size distributions presented in this article are the average of 5 successive particle size analyses. Particle size analyses were performed using a Helium-Neon Laser Optical System Mastersizer 3000 (Malvern Instruments Ltd.) coupled with a Hydro Extended Volume (EV) sample dispersion unit.

Particle size distribution is typically defined using several data points (passing or retained weight%), which represent potential responses to model using the DOE. However, particle size distributions can be modelled using statistically derived distribution models, which reduce the number of responses. The two most common methods used in mineral processing are the Gaudin–Schuhmann and the Rosin–Rammler models [4]. However, these models are typically applied to comminution studies, which often deal with non-uniform size distributions. Thus, even if these models proved to be very accurate, comparisons with other distribution models suggest that a 2-parameter Gompertz model [20], which is a special case of the more general logistic curve, provides the best fit to our data. The Gompertz model is generally