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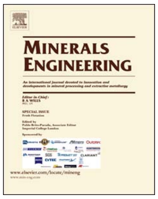

An investigation on laboratory Knelson Concentrator separation performance: Part 1: Retained mass modelling

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ABSTRACT

The retained mass of material in the Knelson Concentrator (KC) bowl depends on the main forces—the fluid drag force (F_d), the centrifugal force (F_c), and the buoyancy force (F_b)—which act on the particles in the concentrating bowl. They are functions of the material properties, as well as the operating condition parameters. In this experimental study, the fluid drag force (F_d) experienced by a solid particle in the rotating bowl was estimated by the fluidization water pressure (P_w) multiplied by the projected area (A_p) of a spherical particle hydraulically equivalent to the solid particle, and used in the model fitting. Quartz, magnetite, zinc, copper, and lead powders were used in different sizes as minerals with the same density to investigate and model the retained mass of material in the KC bowl. By defining the new ratio of $F_d/(F_c–F_b)$, the retained volume of the different materials in the KC bowl was modelled, and it was shown to be the same for a given value of $F_d/(F_c–F_b)$ ratio. Based on the developed experimental database consisting of 284 tests, a Weibull model was proposed. It can accurately model the retained mass of material in the KC bowl for particles with various sizes and densities under a given operating condition.

1. Introduction

In gravity concentration, gravity and centrifugal forces are used to separate the desirable mineral in a mixture of particles of various sizes, shapes, and densities. This method has some advantages over other separation methods, such as flotation and cyanidation, which are expensive, environment-polluting, and relatively complex. These advantages include lower energy and installation costs, and fewer environmental problems. While gravity methods cannot totally replace some separation processes, such as flotation, they can, however, be used in the processing circuits to reduce the circuit size, the use of chemical reagents, and the environmental impact. Gravity separation can also offer the possibility of recovering the heavy minerals that still remain in the flotation tailings (Koppalkar, 2009; Koppalkar et al., 2011; McLeavy et al., 2001).

The first and very crude Knelson Concentrator (KC) was commercialized in 1980 in Canada by Byron Knelson (Anastasakis, 2014; Knelson and Edwards, 1990; Ling, 1998; McLeavy, 2005). The KC has been successfully used to recover gold from various ore types, including placers and hard rock sources. It gained worldwide acceptance because of its remarkable ability to achieve very high gold recoveries over a wide size range (Zhang, 1998). KCs can achieve 96% recovery for free liberated gold particles that are coarser than 30 μm (Coulter and Subasinghe, 2005; Silva, 1986).

Laplante did pioneering research on the KC, and, in particular, its application in gravity-recoverable gold (GRG) determination (Laplante and Doucet, 1996). A standardized test to determine GRG was designed and tested on a wide variety of ores. The results can be used to assess the pertinence of using gravity recovery and to guide in circuit design. For a plant in which gravity recovery is already installed, the test can be coupled with a gravity-recovery simulator to assist in the optimization of the gravity circuit (Laplante, 1998; Laplante and Doucet, 1996). Laplante (2000) devised a method to evaluate the feasibility of employing a gravity gold circuit based on the GRG content.

The KC may be used to recover heavy minerals in alluvial mining and the products of grinding and flotation circuits. In addition, it is used to upgrade tailings, for the secondary recovery of heavy mineral concentrates, and the recovery of heavy minerals and materials, such as mercury, platinum, silver, tantalite, and precious metals. Recently, it has found application in the removal of ash and sulphur from coal (Knelson and Jones, 1994; Laplante et al., 1994; McKenzie, 1997; McLeavy, 2005).

2. Background

Based on Newton's second law, the movement of a spherical particle

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in fluid under the action of a centrifugal field and the forces acting on settling can be incorporated in Eq. (1).

$$F_c - F_d - F_b = m\left(\frac{dv}{dt}\right) \tag{1}$$

in which m is the mass of the particle, $\left(\frac{dv}{dt}\right)$ is the resulting acceleration of the particle, F_c is the centrifugal force, F_d is the drag force, and F_b is the buoyancy force that can be expressed as follows:

$$F_c = \left(\frac{\pi}{6}\right)D^3\rho_s r\omega^2 \tag{2}$$

$$F_d = 3\pi\mu D\left(\frac{dr}{dt}\right) \tag{3}$$

$$F_b = \left(\frac{\pi}{6}\right)D^3\rho_w r\omega^2 \tag{4}$$

in which r is the radial position of the particle of size D; ρ_s is the particle density; ω is the angular velocity; μ is the viscosity of the water; $\left(\frac{dr}{dt}\right)$ is the instantaneous radial velocity of the particle; and ρ_w is the density of water. Substituting Eqs. (2)–(4), and the inertial term on the right-hand side in Eq. (1), one can write the equation of motion of a spherical particle settling radially in the KC as:

$$\left(\frac{\pi}{6}\right)D^3(\rho_s - \rho_w)r\omega^2 - 3\pi\mu D\left(\frac{dr}{dt}\right) = \left(\frac{\pi}{6}\right)D^3\rho_s\left(\frac{d^2r}{dt^2}\right) \tag{5}$$

The inertial term on the right-hand side of Eq. (5) can be neglected, or when the instantaneous velocity is close to the terminal settling velocity, the magnitude of the instantaneous velocity $\left(\frac{dr}{dt}\right)$ will be:

$$\frac{dr}{dt} = \frac{D^2(\rho_s - \rho_w)r\omega^2}{18\mu} = \frac{D^2(\rho_s - \rho_w)g}{18\mu}\,\frac{r\omega^2}{g} = v_g\frac{r\omega^2}{g} \tag{6}$$

in which v_g is the terminal settling velocity of the same particle in the gravitational field. Thus, the instantaneous velocity $\frac{dr}{dt}$ in a centrifugal field is equal to the terminal settling velocity v_g in the gravitational field, multiplied by a factor of $\frac{r\omega^2}{g}$. Therefore, the relation between the centrifugal settling and the gravitational settling can be expressed as:

$$v = Gv_g \tag{7}$$

in which G is the relative centrifugal force, defined as the ratio of the centrifugal force to the gravitational force. Eq. (7) is valid only for the Stokes region (Coulter and Subasinghe, 2005; Koppalkar, 2009; Ling, 1998; Majumder and Barnwal, 2006).

Initially, several researchers at McGill University performed various scientific studies related to KC under the supervision of Laplante, including ore feed characterization (Woodcock, 1994), the evaluation of gravity circuit performance (Putz, 1994; Vincent, 1997; Zhang, 1998), the fundamentals of semi-batch-centrifuge operation (Buonvino, 1993; Huang, 1996; Ling, 1998; Xiao, 1998), and the effects of gold-particle size and wash-water pressure on gold recovery in the KC (Liu, 1989). Furthermore, Laplante (2000) reported a study on the mechanism of upgrading the KC.

Gold gravity recovery has evolved significantly over the last 20 years, largely because of the advent of the KC. Some studies related to the modelling of the KC are illustrated in Table 1.

A mechanistic model was developed by Coulter and Subasinghe (2005) to describe the operation of a KC. They postulated that both centrifugal and Bagnold forces are strongly related to bowl rotation, and their combined effect may be represented by a net force (F_c^*). It may, therefore, be postulated that the probability of a particle being retained within the concentrate chamber must be dependent on the relative extents of F_c^* and the fluid drag force, F_d.

$$X = \frac{F_d}{F_c^*} \tag{8}$$

A Weibull distribution was fitted to the data using the least squares approach. The data obtained in this study represent an individual particle size distribution, only two densities, and a limited range of rotational speed (Coulter and Subasinghe, 2005).

$$V = V_0.\,\exp\left[-\left(\frac{X}{X^*}\right)^n\right] \tag{9}$$

in which V is the volume of the collected material (cm^3); V_0 is the maximum volume of material that can be collected within the KC bowl under a given set of operating conditions (cm^3); X^* stands for the critical value of X at the transition between the two regions; and n is the exponent.

$$V_0 = 4.3 \times 10^3\rho_s D - 2.15\rho_s + 31.23 \quad (R^2 = 0.98) \tag{10}$$

while n may be considered as a constant since none of the operating variables in the regression shows a statistically significant effect (Coulter and Subasinghe, 2005).

$$n = 3.25 + 4.55 \times 10^{-2}\omega - 0.8\rho_s + 5.85 \times 10^5 D^2 - 2.1 \times 10^{-4}\omega^2 (R^2 = 0.92) \tag{11}$$

Therefore, by applying this model, it is possible to obtain the volume of the retained materials (Coulter and Subasinghe, 2005).

From the literature survey done by the authors, the following conclusions could be made:

- Most of the studies on the KC are on gold separation.
- Previous studies were mostly done on tungsten (a material with a density very close to that of gold) and magnetite in the presence of quartz as the gangue, but other materials with different densities have not yet been used.
- Recent studies on the modelling of the KC have been done with only two materials of different densities (magnetite and quartz), and the volume of the material retained in the KC bowl was modelled for each material.

As mentioned earlier, several studies on mineral separation, including gold, platinum group metals, and coal, were carried out using the KC to evaluate the recovery of these materials. The relationship between the centrifugal force (intensity of G-force) and feed properties (density, size, and shape) has not yet been figured out, and the role of bed fluidization water has not yet been studied (Majumder and Barnwal, 2006). Hence, the main objective of this article is to propose an empirical model for the recovery of materials of different densities and particle sizes in the KC in different operating conditions. The next step would be to generalize this model so as to obtain a method to recover materials of varied densities and particle sizes in the KC bowl.

3. Material and methodology

3.1. Materials

To investigate and model the amount of the materials retained in the KC bowl, quartz (Silica Sand MFG Co., Iran), magnetite (Sangan iron ore mine, Iran), zinc (Cirda Co., China), ferromolybdenum (Zanjan Boronz Co., Iran), copper (Khorasan Powder Metallurgy Co., Iran), and lead (National Iranian Lead and Zinc Co, Iran) powders were used in different sizes so that they could mimic minerals with the same densities (Table 2).

All the tests were done using a laboratory KC of the manual discharge type with a bowl diameter of 3 inches (KC-MD3) at the Iran Mineral Processing Research Center (IMPRC). Since the feed and water flow rates have little effect on bowl filling, they were adjusted to 300 g/min and 700 cm^3/min respectively in all the tests. Moreover, a variety of fluidization water pressures (from the highest to the lowest possible value at which overfilling occurs) were applied at rotational speeds of