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Physical analysis and modeling of the Falcon concentrator for beneficiation of ultrafine particles

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ABSTRACT

A predictive model of the Falcon enhanced gravity separator has been derived from a physical analysis of its separation principle, and validated against experimental data. After summarizing the previous works that led to this model and the hypotheses on which they rely, the model is extended to cover a wide range of operating conditions and particle properties. The most significant development presented here is the extension of the analytical law to concentrated suspensions, which makes it applicable to actual plant operating conditions. Two examples of industrial use cases are described and studied by interrogation of the model: dredged sediment waste reduction and coal recovery from fine tailings. Comparisons with empirical studies available in the literature show a good agreement between model predictions and industrial data. The model is then used to identify separation efficiency limitations as well as possible solutions to overcome them. These two examples serve to show how this predictive model can be used to obtain valuable information to improve physical separation processes using a Falcon concentrator, or to evaluate Falcon separator's abilities for new applications.

1. Introduction

Falcon concentrators are enhanced gravity separators (EGS) consisting of a fast spinning bowl. The bowl is fed from its bottom and uses centrifugal force to drain the slurry in a thin flowing film at its wall. During operation, part of the transported particles is retained inside the bowl, while the other part flows out with the fluid. Due to high rotation rate, the centrifugal force in the flowing film can be several orders of magnitude greater than Earth' attraction. Different mechanisms have been identified as playing significant roles in the separation taking place inside the bowl (McAlister and Armstrong, 1998; Laplante et al., 1994; Laplante and Nickoletopoulos, 1997; Laplante and Shu, 1993; Deveau, 2006; Abela, 1997), such as particle differential settling in the bottom region of the bowl, near the film inlet (Zhao et al., 2006).

Three bowl series differ by the way they trap particles once particles have been classified by differential settling in the flowing film. Falcon SB series uses fluidized annular grooves upstream of the bowl outlet. The retention capacity of the bowl can thus be set by adjusting the counter-pressure flow rate. Falcon UF series uses smooth bowls with a slight reduction in diameter at the outlet. This lip creates a non-flowing region whose volume varies with the bowl's opening angle (Holtham et al., 2005). In this case, the film flows over a retention zone that has no fluidization counter-pressure. Both series are essentially semi-batch: "heavy" particles are recovered by interrupting operation and emptying the retention zone before a new operating cycle starts. The third design – C series – operates similarly to the UF series, but adds a slot in the retention zone that is equipped with discharge valves with variable size apertures. In this way, the discharge rate in the retention zone can be adjusted, which makes it possible to operate the bowl continuously (McAlister and Armstrong, 1998; Honaker et al., 1996; Abela, 1997).

Commercial brochures published by Falcon indicate recovery abilities for C and UF series down to 10 and 3 μm respectively for targeted applications to heavy materials (tin, tantalum, tungsten, chrome, cobalt and iron). The UF series are more limited in terms of capacity (up to 20 m^3/h for the bigger bowls) due to their design oriented towards ultrafine particle recovery. This study focuses on these concentrator series because of their potential application to fine dredged sediments. Nevertheless, a number of conclusions drawn from physical analysis of these concentrators remain valid for other series.

2. Separation modeling

2.1. Physical analysis and hypotheses

The assumptions on which our modeling of the smooth-wall Falcon device relies, have already been described in previous publications (Kroll-Rabotin et al., 2010, 2011a, 2011b; Kroll-Rabotin, 2010). The fundamental hypothesis on which our modeling is based is that once particles enter the bowl retention zone, they never leave it. Moreover, any

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classification upstream of the flowing film is neglected: it is assumed that the impeller at the bottom of the bowl plays no active role in the separation — ot is considered in fact that it homogenizes the feed that enters the flowing film. Suspension is then considered homogeneous at the film inlet which implies that the prevalent separation mechanism is particle transport in the flowing film before particles reach the retention zone or the bowl outlet. Our predictive model was then built by solving a simplified particle transport equation analytically.

The evolution of the flowing film thickness along the bowl wall is neglected, so that the flow is modeled by the combination of a semi-parabolic profile in the streamwise direction and a solid body rotation. This simplification is discussed in Section 2.2.

Once the flow has been modeled, a transport model is added to it in order to predict separation. To achieve this, numerical and analytical solutions of Lagrangian (Kroll-Rabotin et al., 2010), and Eulerian tracking of particles in the film were obtained (Kroll-Rabotin et al., 2011a).

The analytical solution is obtained by neglecting particle interactions. Therefore, it is only reliable to predict separation in dilute suspensions. Particle transport is then governed by the balance between drag and centrifugal forces acting on particles. For this balance to be sufficient to account for the real physics, particle inertia must be neglected. Also, in order to get an analytical solution, the drag law must remain linear. These two assumptions limit analytical predictions to low Stokes and low particulate Reynolds numbers. However, it is shown in Section 3.2 that it does not affect the accuracy of the model.

Finally, the recovery of a given particle type – characterized by its radius (r_p) and density (ρ_p) – in a smooth wall Falcon bowl is given by:

$$C_p = \min\left(\frac{4\pi}{9}\lambda Q^{-1}\omega^2\left(\rho_p-\rho_f\right)r_p^2\mu^{-1}R_{\min}R_{\max}H_{bowl},1\right) \quad (1a)$$

where C_p is the equation of the partition surface. In this equation Q and ω are the operating conditions (feed and bowl rotation rates), ρ_f and μ are the carrier fluid properties (density and dynamic viscosity). $R_{\min}$, $R_{\max}$ and H_{bowl} define the bowl geometry (base radius, radius at the outlet and height) and λ is a calibration constant. Experiments yielded a value of $\lambda = 0.68$ for a laboratory scale Falcon L40 equipped with a UF bowl (Kroll-Rabotin et al., 2011b). The need of a calibration constant has already been detailed extensively in Kroll-Rabotin et al. (2011b): it actually only reflects the simplifications we have included in the model derivation such as:

- bowl geometry (as it is simplified to the 3 parameters $R_{\min}$, $R_{\max}$ and H_{bowl}, while actual bowls are made of a few parts with different opening angles, include trapping mechanisms, etc.);
- rotation as a solid body (which may contain up to almost 10% error as stated in Section 2.2);
- other neglected terms detailed in the model derivation.

Among those three points, the first one seems to be the most significant, and is the reason why the calibration should be evaluated for each bowl shape (which differs slightly between bowl sizes and Falcon series). The fact that the calibration constant's order of magnitude is around unity confirms that it only contains corrective terms and does not hide any unaccounted significant physical phenomenon.

It is worth mentioning that due to the balance between drag and centrifugal forces, theoretical particulate Reynolds number and Archimedes number are related. For particles whose settling follows Stokes' drag law, $Re_p = (3\pi)^{-1}Ar$. Because of that, it is commonly said that particulate Reynolds number governs separation in gravity separators. This is not effectively true in this case as it does not accurately account for the effects of flow rate and particle size, as shown is this other form of Eq. (1a):

$$C_p = \min\left(\frac{1}{3}Ar\lambda Q^{-1}r_p^{-1}\nu RH_{\text{bowl}},\ 1\right). \quad (1b)$$

In this expression, a pseudo Reynolds number appears. It is based on particle size and on velocity $Q/(RH)$ which has no direct physical meaning, since Q is the feed flow rate and $R \times H$ is half the area of the bowl azimuthal section. This simple overview of the model already shows that although such gravity concentrators are used to perform separation according to particle densities, particle size is also playing a significant role in their performances (Coulter and Subasinghe, 2005).

2.2. Modeling of the flow profile

A major difficulty in the flow field computation is the free surface of the film which yields a boundary condition whose position is unknown until the problem is fully solved. It could be solved numerically by interface tracking or with the "*Volume of Fluid*" method (Dijk et al., 2001) that solves the physics continuously between the liquid and gas phases by weighing them according to their respective local volume fractions. This method would make it possible to compute the flowing film thinning along the bowl wall. However, such an approach is only required when the film thickness undergoes significant variations. Another approach that has been described thoroughly in the literature gives analytical solutions of the simplified Navier–Stokes equations in a rotating referential (Bruin, 1969; Makarytchev et al., 1997, 1998; Janse et al., 2000; Langrish et al., 2003).

In a Falcon concentrator, the centrifugal force due to the bowl spinning reaches several hundreds of times the Earth's gravitation (from 100 to 600 G depending on the series). For high Froude numbers Makarytchev et al. (1997) give:

$$h = \left(\frac{3\nu Q}{2\pi\omega^2 r^2 \sin\frac{\beta}{2}}\right)^{1/3} \quad (2)$$

This simplified law expresses how film thickness changes as a function of the operating and geometrical parameters. In particular, expression (2) yields the thickness ratio between the bottom of the bowl (h_i) and the outlet (h_f):

$$\frac{h_f}{h_i} = \left(1+\frac{H_{\text{bowl}}}{R_0}\tan\frac{\beta}{2}\right)^{-2/3}. \quad (3)$$

For a Falcon L40 with a UF bowl, this ratio is approximately 0.8 which confirms the validity of the constant thickness assumption when compared to the shape ratio of the film azimuthal section. It only depends on geometrical properties and is approximately the same for all Falcon series, even for industrial scale bowls. As a result, variations of the film thickness are neglected in our modeling.

In the streamwise direction (parallel to the bowl wall), for high Froude numbers and high rotation rates, the analytical solution given by Makarytchev et al. (1997) is a semi-parabolic profile:

$$u_X \approx \frac{Q}{2\pi rh}P\left(\frac{Y}{h}\right) \quad (4a)$$

$$P\left(\frac{Y}{h}\right) = \frac{3}{2}\left(2\frac{Y}{h}-\frac{Y^2}{h^2}\right). \quad (4b)$$

In the azimuthal plane, the only simplification that was added to the analytical solution is the constant film thickness, so wall-normal fluid velocity is neglected:

$$u_Y = 0. \quad (5)$$

The only shear source in the azimuthal direction is Coriolis acceleration. Indeed, fast rotation speed may induce significant Coriolis effects that make the flow fully three-dimensional. The azimuthal velocity profile is also given by Makarytchev et al. (1997) as:

$$u_\theta = \omega r\left(1+\frac{1}{4}Ek^{-2}P_\theta\left(\frac{Y}{h}\right)\right) \quad (6a)$$