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Hydrocyclone equivalent settling area factor at higher concentrations and developing a performance chart

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ABSTRACT

The equivalent settling area factor allows for comparison amongst different centrifuge separators. For hydrocyclones, the so far developed factor does not consider the effect of concentration of solid particles c in the feed stream, because particle interactions at high concentrations cause hindered settling and reduce hydrocyclone performance. The focus of this paper is a modification of this factor to allow prediction of the influence of higher particle concentration in the feed stream. In particular, the equivalent area factor is modified at high particle concentration by applying different forms of hindered settling concentration functions and using data obtained from experiment or from existing empirical correlations. This results in a set of modified models that are evaluated using statistical techniques. Through statistical analysis, the function $f(c) = c^{0.0488}\exp(-9.445c)$ is selected to modify the equivalent settling area for hydrocyclones. A performance chart is developed for hydrocyclones by undertaking the modified equivalent area model that can be used in hydrocyclone design applications. The developed performance chart is validated and is shown to be capable of predicting the hydrocyclone performance over a wide range of hydrocyclone flow rates and separation cut sizes. This chart is compared with a performance chart available in the literature and the chart in the literature is shown to over-predict the hydrocyclone performance.

1. Introduction

The equivalent settling area factor has been developed as a mathematical tool to compare the performance of different centrifugal separators [1–3]. This factor allows comparison and scale-up of centrifugal separators, which is important in the selection and design process. The equivalent settling area factor is defined in relation with flow rate Q and particle settling velocity v_g such that [1]:

$$Q = 2v_g\Sigma \tag{1}$$

and

$$v_g = \frac{\Delta\rho d^2 g}{18\mu} \tag{2}$$

where $\Delta\rho$ is the density difference between liquid and solid, d is the particle diameter (which is typically 50% cut size particle size), and μ is the fluid viscosity.

The factor is also developed for solid-liquid separation in hydrocyclones [4–8] and can be used as a criterion for comparing the hydrocyclone performance with other types of centrifugal separators. This factor in hydrocyclones is based on residence time theory [9], which in turn predicts the 50% cut size particle in separation. The importance of developing such a factor for hydrocyclones and its application in centrifugal technology is detailed in [7,8]. The version of the equivalent settling area model (ESAM) developed to date [8] does not consider the effect of concentration of solid particles in the feed stream.

It has been observed that the performance of a hydrocyclone is affected by the solids concentration in the feed. A high concentration of solids in the hydrocyclone leads to lower settling velocity [10] as compared to the Stokes settling velocity. The influence of inlet solid concentration on the hydrocyclone performance has been studied theoretically and experimentally [11,12]. Increasing the feed concentration while keeping all other parameters constant results in more particles in the overflow and coarser particles in the underflow [11]. This has been attributed to hindered particle motion in the radial direction where particles move toward the wall [11]. Limited capacity of the underflow diameter and changes in the flow field [13] are listed as other reasons for entrainment of

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the particles in the hydrocyclone. This eventually leads to less efficient separation. A reduction in pressure drop at higher flow rates has also been related to the effect of hindered settling [11].

To correlate the influence of the hydrocyclone design and operating variables, including solids concentration in the feed, several studies have been undertaken. Lynch et al. [14] and Plitt [15] developed empirical models that are widely used in hydrocyclone development. Such models are generally restricted to the specific hydrocyclone dimensions, range of operation, and material properties used to parameterize the model. For instance, the Plitt model has been reported to be incapable of predicting the pressure drop and corrected cut size with low solid fraction in some experiments [16,17]. While some correlations represent the concentration effect through a function obtained from the regression analysis (as in Plitt model), in some researches the settling velocity of the particles is modified for the hindered conditions. Using the ratio of free to hindered terminal settling velocity for spherical particles [18], a set of correlations with constant coefficients only depend on feed solid characteristics was developed [19].

For families of geometrically similar hydrocyclones, including Bradley and Rietema hydrocyclones, a model is generated based on dimensionless groups to predict hydrocyclones performance [20]. Although this model is limited to certain aspect ratios and hydrocyclone diameters from 22 to 122 mm, it has the advantage that it does not need to be adjusted for each application. Therefore, similar to the Plitt model [15], it is a useful model that can be applied irrespective of the material fed into the hydrocyclone. However, the Coelho model [20] is expected to give a better prediction for the materials used in model development. Feed volumetric solid fraction varies from 0 to 0.1 for this model which - unlike some other models - allows prediction of the performance for low concentrations. This model has been reported [20] to be capable of reproducing data from Kelsall [21], Bradley [22] and Rietema [23–26].

An extensive investigation for the effect of solid concentration and other influential factors has been undertaken by researchers at the Julius Kruttschnitt Mineral Research Centre (JKMRC) at the University of Queensland [27–30]. Using the data of JKMRC with the feed solid weight fraction of 14–70% and hydrocyclone diameter ranging from 10–75 cm, a model that includes the effect of hydrocyclone inclination is described [31]. Combining a variety of experimental data sources for small- and large-scale hydrocyclones and undertaking a computational fluid dynamic (CFD) simulation, a semi-mechanistic model has been developed for hydrocyclones based on multiple linear fitting approach for estimating model parameters [32]. A set of application-dependent system constants has also been inserted into the model that must be determined for each new application. This model takes the effect of feed volume concentration into account, including the equation proposed for hindered velocity [18].

The performance of centrifugal separators is typically compared through the equivalent settling area factor [7,33]. This is the area of a gravity settling tank that yields the same performance as the centrifugal separator device under the same operating conditions. The performance of hydrocyclones as a type of centrifugal separator in terms of the equivalent settling area at high particle concentration has not been studied. Considering the Stokes flow and a cut size particle in a hydrocyclone, an equivalent settling area model has been developed [8]. This model can be extended for the influence of solid concentration in the feed stream.

Typically, increasing the concentration brings the particles closer to each other, which in turn allows them to cluster. This should increase the settling velocity; however, for flows such as in hydrocyclones where the shear rate is high, the cluster does not survive and the settling rate reduces with increasing concentration [34]. Increasing the inlet solid fraction results in a decrease in the separation efficiency [35]. High solid concentration increases the particle-particle interactions and hence reduces the particle settling velocity to what is known as the hindered settling velocity [11]. This velocity is usually related to the Stokes settling velocity [10] and is a function of concentration [36] such that:

$$v_h = v_g f(c) \quad (3)$$

where v_h represents the hindered settling velocity, f is a function of concentration and c is the fraction of solid volume concentration in the mixture [37]. A well-known relation for the effect of concentration on Stokes (gravitational) settling velocity has been proposed by Richardson and Zaki [38]. It has been observed that the settling velocity changes with changes in the solid fraction c in the mixture such that the Stokes settling velocity v_g is corrected by the multiplicative factor $(1-c)^k$, where k is a coefficient that is experimentally determined to be 4.65 [38]. Other research works have also addressed this subject [18,36,39–41]. A method for determining k is presented in [40] which is dependent on the solid material properties and may vary significantly from what is suggested by Richardson and Zaki [38]. For sand particles, a review of the settling models can be found in Zeidan et al. [37].

Modeling the effect of solid concentration in hydrocyclones has been done in the literature by applying a function of solid volume fraction in the mixture c into a hydrocyclone performance model [20,42–45]. Some investigators have adopted the Richardson and Zaki [38] hindered settling correlation into their hydrocyclone models [42,46] while others have formed different nonlinear relationships from a gravity settling formulation [44,47]. Most models are based on experimental correlations as the theoretical solution for the effect of hindered settling is complex. The experiments and resulting experimental correlations for sets of different designs of hydrocyclones, [20] shows that concentration affects the hydrocyclone performance parameters (such as pressure drop, flow rate, and cut size).

The developed ESAM [6–8] is based on residence time theory, which does not take the concentration and hence hindering effect into account, such that:

$$\Sigma = \beta \frac{L\Delta P}{\rho g} \quad (4)$$

and

$$\beta = \frac{\pi n[1-(D_o/D)^2]}{(D/D_o)^{2n}-1}\left(\frac{1}{1-D_i/D}\right)^{2n+1} \quad (5)$$

where Σ is the equivalent area factor from ESAM, ΔP is pressure drop, ρ is liquid density, L is hydrocyclone total length, D_o is overflow pipe diameter, D_i is inlet pipe diameter, D is the diameter of the cylindrical portion of the hydrocyclone, and n is an experimental exponent that appears in the tangential velocity component [9]. The equivalent diameter to a circular pipe is used in Eq. (5) by equating the inlet section area to the area of a circular pipe. Mathematically Eq. (5) is valid if the following conditions hold: $D_o/D > 0, D_i/D < 1,$ and $D_o/D \neq 1$. Physically, $(2D_i/D + D_o/D) \leq 1$ can be considered to be a limit for the inlet pipe and the vortex finder diameters [6,8].

This study modifies the ESAM, Eq. (4), to allow predicting the separation performance at high concentrations when hindered settling occurs. This is done by applying different forms of hindered settling concentration functions in the ESAM. The function that provides the best prediction is obtained through regression analysis by comparisons between the empirical data and predictive models. The modified equivalent settling area model (modified ESAM) for the effect of concentration is denoted as Σ_c and is used to evaluate the effect of operating and performance parameters in hydrocyclones. This model (Σ_c) is used to develop a performance