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Exploring the interplay between abrasive attrition and separation in cyclones

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ABSTRACT

It is widely known that higher cyclone inlet velocities produce a finer and tighter gas–particle separation at the cost of higher particle attrition. Few models exist that study the simultaneous interplay between these two effects in detail. In this work we present a series of progressively more complex models of abrasive attrition and cyclone separation in a circulating fluidized bed (CFB) riser.

The simplest of these models treats the in-situ particle size distribution (PSD) as that of the feed material, computes attrition based on a constant diameter reduction rate with instantly vanishing fines, and uses a simple two parameter cyclone grade efficiency model. This simple model is studied as a function of feed PSD, relative attrition rate, and cyclone grade efficiency parameters. The consequences of adding more complexity to the model – via a population balance (PB) computation of the true in-situ PSD, size dependent attrition, non-vanishing attrited fines, more detailed cyclone modeling, etc – are examined as well.

The purpose of these exercises is to understand the mechanistic interplay between attrition and cyclone separation efficiency and evaluate the necessity of increased model complexity for accurate prediction. From this work, it was determined that in many practically operated regimes (relatively low attrition and reasonably low cut sizes) all models give roughly the same results. However, the more complex models are useful for understanding upset and worst case scenarios as well as for systems designed in other operating regimes.

1. Introduction

Generally it is well understood that there is a strong influence of cyclone inlet velocity on both collection efficiency and particle attrition within the cyclone. Determining the optimum cyclone geometry and operating conditions (e.g. inlet velocity and solids loading), therefore, requires consideration of both of these mechanisms. Typically, this problem falls under the art side of cyclone design. While there exists literature on particle attrition [1–4] and cyclone collection efficiencies [5,6], there is a surprising lack of literature on the interplay between both mechanisms.

In general, attrition can be classified into two general categories: abrasion and fragmentation. When particles attrite via abrasion, they continuously shrink in size, generating very fine (typically 1–2 μm for FCC type catalyst, but can be >10 μm for some materials) attrited material along the way. Fragmentation occurs at higher energy and results in a particle breaking into two or more fragments along with fines generated at their interface. In systems that have been designed to limit solids loss, generally abrasive attrition dominates and fragmentation may be ignored [1,3,4]. Therefore, in this work, only abrasive attrition is considered.

Even within the abrasive attrition literature there are questions as to how particles of varying size attrite. The size dependence of particle attrition has been addressed by several authors [4,7] resulting in a number of different size dependence models. If a particle attrits such that the mass of fines generated is proportional to its surface area, the rate at which its diameter reduces will be independent of particle size. However, empirical data suggests that the rate of diameter reduction can be constant, proportional to particle size [8], or even proportional to the square of particle size [9].

Most studies avoid accounting for collection of attrited fines by assuming that the generated fines have effectively zero size, and are always instantly lost from the system [10–12]. On the other hand, Ray et al. [4] have proposed the concept of a natural particle size that the fine material abrades down to. It has been shown that regardless of initial particle size or abrasive attrition intensity, the particle size distribution of the attrited fines remains the same [1,4]. This mechanism is rarely accounted for in the literature. Montagnaro et al. [13] included a natural PSD, as well as unattriable fines, in their model of a fluidized bed combustor. However, they did not report the effects of this assumption alone, only the effects of accounting for attrition at all.

It is also widely recognized that fresh catalyst attrits at substantially faster rate than equilibrium catalyst [1,4,9,12]. In batch processes the decreasing attrition rate can be modeled as a function of time [1]. However, in a continuous operation, the age of catalyst is less easily

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determined. Hartge et al. [12] account for these unsteady attrition effects by tracking an intermediate "dimensionless stress history" parameter, which is roughly equivalent to catalyst age. Very few models, besides Hartge et al. [12], account for the unsteady attrition mechanism.

The current authors could only find a single study coupling collection and attrition directly. Reppenhagen et al. [14] studied a portion of the problem when they examined the relation between attrition and collection for a cyclone at the end of a pneumatic conveying line. Here they found, discounting attrition, that the cyclone separation efficiency would asymptote towards 100% as inlet velocity was increased (for fixed cyclone geometry and solids loading). However, when particle attrition was accounted for, the total collection efficiency curve goes through a maximum. This maximum efficiency is expected to be a function of the attritability of the particles. Highly attritable particles will generate more fines at a lower inlet velocity, resulting in a lower overall collection efficiency. As the attritability of the particles decreases, the collection efficiency increases, approaching the efficiency expected from unattritable fines. The optimum inlet velocity is, therefore, a function of the attritability of the powders to be separated.

The system studied by Reppenhagen et al. [14] only considered the impact of attrition due to a single pass through the cyclone (since it was considered at the end of a conveying system). In a fluidized bed system, particles will have many passes through the cyclones as they attrite down and are eventually lost. The feed particle size distribution, attrition rate, and cyclone collection efficiency will govern the equilibrium particle size distribution [10]. Also, similar to other studies, their model implicitly assumed that all fines are lost by the cyclone.

Therefore, in this work, we examine the combined effects of attrition and cyclone separation at equilibrium conditions by means of a population balance (PB) model. This allows determination of the equilibrium particle size distribution (and resulting separation efficiency), rather than basing prediction on a single point in time (e.g. the starting conditions). The model will be made progressively more complex by incrementally adding mechanisms so that the influence of each mechanism may be explicitly understood.

No new models will be presented in this work, only an analysis of the consequences of existing models. Therefore, no experimental data is shown for comparison or validation. Nevertheless, that does not diminish the utility of this work as it demonstrates the interplay and competition in a complex particulate system.

2. The model

2.1. The model system

The system to be modeled consists of a riser with a close coupled cyclone (Fig. 1). It is assumed that all of the attrition occurs due to the cyclone, and that all of the material in the bed continuously passes through the cyclone at a rate $\dot{M}$. For clarity, this model only considers classification from the cyclone itself. That is, close coupling the cyclone avoids the added complexity of bed entrainment as an additional classification mechanism.

The system is considered to be under steady state conditions, such that the solids loss rate L matches the continuous feed rate F. The important dependent variable for this study is the overall cyclone collection efficiency $\eta = (\dot{M} - L)/\dot{M}$. The value of η can be computed knowing the particle size distribution (PSD) of particles fed to the cyclone and the cyclone grade efficiency curve, $G(x)$ [6]. The value $G(x)$ gives the fraction of particles of size x fed to the cyclone that are captured. The relation between $G(x)$ and η is simply $\eta = \int G(x)y(x)dx$, where $y(x)dx$ gives the mass fraction of particles fed to the cyclone with size between x and $x + dx$.

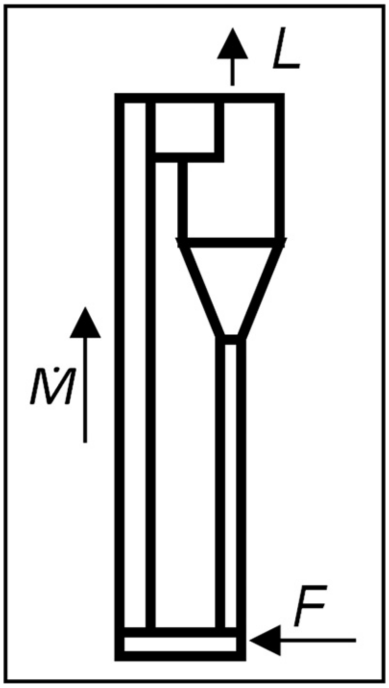

Fig. 1. System schematic.

2.2. The population balance (PB) equation

In order to compute the equilibrium particle size distribution we must use a PB model. A PB model is effectively a mass balance on each differential size class of particles in the system. For a general discussion on PB equations see Hulburt and Katz [15], Randolph and Larson [16], or Ramkrishna [17]. For a derivation similar to that used in this work see Levenspiel et al. [10]. We begin by defining the function $m(x)$ so that $m(x)dx$ represents the mass of material in the system with size between x and $x + dx$. Naturally, we have $M = \int mdx$, where M is the total system mass and $y = m / M$. In this case, our mass balance is written as,

$$\frac{\partial m}{\partial t} = \left[\frac{\partial}{\partial x}(Rm) - 3\frac{Rm}{x}\right] - \dot{M}\,(1-G)y + Fy_F \tag{1}$$

where R is the diameter reduction rate due to attrition (e.g. μm/h), and y_F is the feed particle size distribution (1/μm). The term on the left hand side of Eq. (1) represents the unsteady mass change in a particle size class. The brackets on the right hand side account for mass changes due to attrition. In the brackets, the first term accounts for mother particles leaving size class x (to go to the adjacent smaller class) due to attrition, as well as mother particles that have attrited down from the adjacent larger size class. The second term within the brackets accounts for mass loss in a size class due to daughter particles leaving. As this equation is written, the daughter particles are assumed to instantly vanish. This will be refined later. Mass that cannot be captured by the cyclone is accounted for by the first term to the right of the bracketed term. Again, we assume that the whole system travels through the cyclone, with no segregation, so the mass flow rate is $\dot{M}$and the size distribution is simply the system size distribution y. Finally, the last term on the right hand side accounts for mass addition at a rate F of particle with the feed particle size distribution y_F.

Integrating Eq. (1) over all possible sizes results in the macroscopic mass balance equation (see Appendix I for details),

$$\frac{dM}{dt} = -3\int_{x=0}^{x\to\infty}\frac{Rm}{x}dx - \dot{M}\int_{x=0}^{x\to\infty}(1-G)ydx + F \tag{2}$$