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The spiral jet mill cut size equation

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ABSTRACT

Micronisation, or fine grinding, is a key unit operation for many industries, with the spiral jet mill being popular as it is robust and reliable. Within this paper an analytical derivation for spiral jet mill cut size as a function of micronisation settings, gas thermodynamic properties and empirically derived constants for the material and mill is presented for the first time. This has been corroborated by experimental evidence and previously reported data in the academic literature and provides an insight into the interaction between aerodynamic particle classification and fine grinding. A scale up methodology is proposed for a high value material by using a small scale mill to determine the material specific constants of the high value material and a cheaper surrogate material to determine mill specific constants at increased scale.

1. Introduction

1.1. Context

Micronisation, or fine grinding, is a key unit operation for a number of industries with the spiral jet mill being popular as it is robust and reliable. Despite the spiral jet mill being a well established and widely applied technology, there are no proven scale up methodologies. Scale up of the spiral jet mill is still possible by empirical iteration to achieve a desired particle size at increased throughput, however this can be wasteful and is particularly undesirable for high value materials. Additionally, the interaction between aerodynamic particle classification and fine grinding in a spiral jet mill is not fully understood within the academic or industrial community, making informed optimisation of mill design challenging.

Within this paper an analytical derivation for spiral jet mill cut size as a function of micronisation settings, gas thermodynamic properties and empirically derived constants for the material and mill is presented for the first time. The derivation is corroborated by experimental evidence and previously reported data in the academic literature and provides an insight into the interaction between aerodynamic particle classification and fine grinding. The constants within the equation can be determined empirically for a given material and mill, leading to a better prediction across a design space than standard empirical models. A scale up methodology is proposed for a high value material by using a small scale mill to determine the material specific constants of the high value material and a cheaper surrogate material to determine mill specific parameters at increased scale.

1.2. Process description

Grinding in a spiral jet mill is achieved as a result of particle collisions caused by high velocity gas exiting a series of nozzles situated around a grind chamber as per Fig. 1 which shows the plan view and process description of a spiral jet mill and Fig. 2 which shows a side view. The grind chamber is typically cylindrical but may also be elliptical in shape. The nozzles are angled such that gas and particles circulate at high velocity around a central exit, resulting in a centrifugal force which retains particles in the grind chamber until micronised. The spiral jet mill is generally operated at steady state as a semi-continuous process with a controlled solids feed rate and gas mass flow rate. When the solids feed rate and gas mass flow rate are controlled, the spiral jet mill delivers a consistent output Particle Size Distribution (PSD). Micronised material can be collected by a combined vane-less axial entry reverse flow cyclonic separator (bottom discharge system) or other means such as a filter sock or bag (top discharge system).

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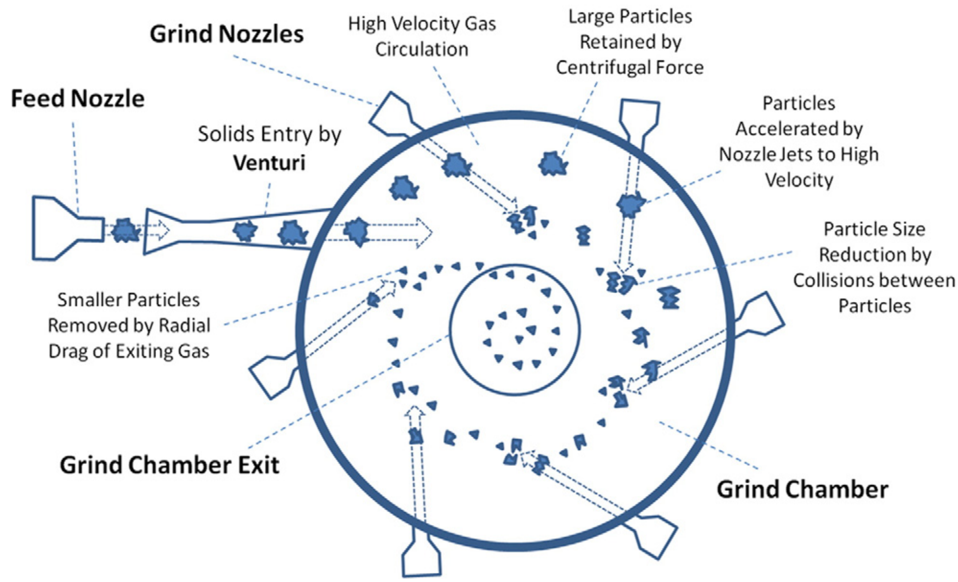

Fig. 1. Spiral jet mill grind chamber (plan view).

1.3. Current literature for estimation of cut size

1.3.1. Underlying physics and numerical simulation

The underlying physics governing particle size obtained from a spiral jet mill were discussed in 1969 by Dobson and Rothwell [1] who noted that output particle size could be estimated by opposing centrifugal and radial drag forces on a particle at the grind chamber exit. Theoretically, the spiral jet mill has a size of particle (d_{cut}) that will remain balanced at the grind chamber exit with equal drag and centrifugal force. Fig. 3 illustrates the forces balance for a particle at the grind chamber exit.

The forces balance can be solved for cut size (d_{cut}):

$$d_{cut} = k_1 \frac{v_r^2}{v_t^2} \tag{1}$$

where $k_1 = 3C_D\rho_g r/4\rho_p$, C_D is the drag coefficient of the particle, ρ_g is the gas density, ρ_p is the particle true density, r is the radial position of the particle, v_r is the gas radial velocity and v_t is the tangential velocity of the particle. The drag coefficient, C_D, is known to vary with both gas velocity and particle diameter and is considered in detail in Section 2.3. Assuming relatively low mass fluxes of powder and high gas tangential velocity, it is possible to assume that the particle tangential velocity equals the gas tangential velocity [2]. In most cases this assumption is valid as the mass flux of powder through the grind chamber exit is generally less than 10 kg/m^{2}s and the gas tangential velocity is much greater than 14 m/s. The Cunningham slip correction factor may need to be considered for very fine particles, however with respect to defining the largest particle that can escape the grind chamber it has not been taken into consideration.

Despite Dobson and Rothwell [1] showing that output particle size is likely to be a function of aerodynamics at the grind chamber exit, their theory offered no explanation for the variation in particle size with solids feed rate or solids mechanical properties. An earlier discussion on milling by Berry in 1946 [3] noted that the solids feed rate could have an impact on the rotational speed in the milling chamber of a spiral jet mill, however this was not investigated further until later [4].

Proposed explanations for changes in particle size with varying solids feed rates in the loop jet mill by Dotson [5] form the basis of subsequent research papers on jet milling [6,7,8]. It is observed that at very low solids feed rates, the mill is in a starved condition where there are not enough particle-particle collisions for efficient size reduction. In this starved state, increases in the solids feed rate result in a reduction in output particle size. Following on from the starved condition, further increases in the solids feed rate result in an increase in output particle size. The proposed explanation for increases in output particle size with increasing solids feed rate, in these papers, is a reduction in collision velocity and energy with increased particle population. A reduction in average particle-particle collision velocity was observed in a 2-D combined Computational Fluid Dynamics and Discrete Element Method (CFD-DEM) simulation by Han et al.[9] and as such this may be a contributing factor to changes in particle size with solids feed rate.

However, changes alone to the collision kinetics do not provide a full explanation for the observed response of particle size to varying gas mass flow rate and solids feed rate. Although the interaction between grinding and aerodynamic classification were further investigated [10], no advancement was made beyond Berry [3] and Dobson and Rothwell [1] until Müller et al. [4] discussed the impact of material held up in the grind chamber (hold up) on cut size. Solids entering the spiral jet mill are retained and continue to accumulate as aerosolised hold up until the number of collisions increases and the output rate of micronised powder is equal to the solids feed rate. As the spiral jet mill operates as a semi-continuous process at steady state, there will be a fixed amount of hold up for a given solids feed rate and gas mass flow rate combination. Müller et al.[4] noted that cut size varied with

Fig. 2. Spiral jet mill grind chamber (side view).