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The effect of particle agglomeration and attrition on the separation efficiency of a Stairmand cyclone

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ABSTRACT

The influence of material properties on the separation grade efficiency of cyclones has long been ignored by researchers. This experimental study investigates the behaviour of two powders of similar density, Kaolin and SAE, in a small scale Stairmand cyclone with inlet velocities of 15, 30 and 45 m s^{-1}. Initially evidence of agglomeration of fine particles occurring within the cyclone body is observed; however, as the inlet velocity increases, particle attrition dominates the behaviour of fine particles in the grade efficiency graphs. Both powders respond similarly to increased flow rates; however, Kaolin exhibits a greater tendency to agglomeration and attrition, which is manifested in the difference between the respective grade efficiency curves, thus demonstrating the complex effect of material properties on cyclone efficiency.

1. Introduction

Reverse-flow cyclones, in the most fundamental respect, are a class of separator that removes particles from an air flow through utilising the effects of the centrifugal force. Robust in structure, relatively inexpensive to construct and requiring little maintenance, cyclones are used for the removal of harmful or nuisance air-borne particulates or liquid droplets. Several studies of small scale reverse-flow cyclones have been undertaken by examining the effects of cyclone design and air flow rate on collection efficiency [1–4]; however none has commented on the effects of particle agglomeration or breakage. Small scale cyclones have a variety of industrial and domestic applications, including cyclonic vacuum cleaners [5], bioaerosol samplers [6], aerosol drug delivery systems [7,8] and the pre-filtration of dust in automobile ventilation [8] and combustion engines [9,10]. Therefore it is of importance to further expand the traditional study of industrial sized cyclones to the small scale, which is the focus of this study.

During a recent collaboration between Cheng and the authors of this paper, data indicative of particle breakage occurring within miniature cyclones for use in dry powder inhalers was observed and reported [7]. In response to these novel results this paper presents, to the best of the authors' knowledge, a unique investigation into particle agglomeration and attrition in a 40 mm Stairmand high efficiency cyclone and examines the influence of particle type, flow rate and dust loading on the separation grade efficiency. As such this study deepens on the understanding of cyclone behaviour and provides results that may influence future cyclone design and operating conditions.

1.1. Cyclone function

The characteristic air flow pattern of a reverse-flow cyclone consists of an inner and an outer vortex, both spiralling in the same sense, with the outer vortex descending into the cyclone, reversing its direction and exiting the cyclone through the vortex finder located in the cyclone roof [11,12]. It is this rotational motion that permits the particles to be carried in the gas, to experience the effects of the centrifugal force, with the particles that possess sufficient inertia being carried to the cyclone wall and separated from the air flow [13–15]. This is however a simplified perspective and belies the profound effects of dust concentration and particle interaction on separation performance.

1.2. Particle agglomeration and dust loading

It is well established that as the concentration of dust within an air flow increases the overall separation efficiency of the cyclone increases while the pressure drop decreases. This improvement in the cyclone performance has been noted to commence at dust loadings as low as 0.00014 kg of chalk dust per m^3 of air, which resulted in the assertion that there is no lower limit of dust concentration which does not demonstrate enhanced cyclonic performance [16]. The improvement in performance with increased dust loading varies with cyclone geometry and

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the inlet velocity. The influence of geometry becomes less important with increased dust loading [17], while lower inlet velocities show greater performance improvement than higher flows [16], although very low velocities do not follow this trend [18].

The mechanism by which increased dust loading improves the overall separation efficiency is not clearly understood; however the two main arguments revolve around theories of critical dust loading and particle agglomeration, with both effects taking place in or immediately after the cyclone inlet. Hoffmann & Stein [19] have given a thorough account of these theories and the papers written in German that appear in this paper are as reported in their book.

Muschelknautz & Trefz introduced and developed the concept of critical or limit dust loading [20–22], which is the quantity of dust that the gas can hold in turbulent suspension. If the quantity of dust entering the cyclone exceeds this limit, then the excess dust is separated in an unclassified fashion and deposited on the walls at or near the inlet. Although there is strong experimental evidence supporting unclassified separation [17], the critical load theory also implies that below this limit load, improvement in separation performance with increased dust loading does not occur; this is however at odds with the observed behaviour [16].

In contrast to the concept of critical load, Mothes & Löffler [23] proposed that particle agglomeration actions the improvement in cyclone performance with increased dust loading. Larger and smaller particles agglomerate, thus making the separation of finer particles from the air stream more likely; this hypothesis is also supported by Ji et al. [24]. There was concern however that agglomeration alone would not account for the magnitude of the effect on separation efficiency [19]. Particle agglomeration within a downcomer tube of a cyclone has been observed by phase Doppler anemometry (PDA) [25], lending credence to the agglomeration hypothesis. However there is agreement that the minima frequently observed in separation grade efficiency graphs, corresponding to finer particle sizes, are indeed a result of the agglomeration of fine particles [19,26,27].

Agglomeration, or coagulation, is the primary inter-particle occurrence between aerosol particles. When aerosol particles collide due to their relative motion, the particles may adhere to each other and form larger particles known as agglomerates. Kinematic coagulation arises when the relative motion of the particle is the result of an external force, such as the centrifugal force as is the case with cyclones [28]. The main adhesive force is the van de Waals force, which is due to complementary dipoles (concentrations in electric charge) forming in neighbouring particles, and producing an attractive force. The surface force also plays a strong role. This force arises from liquid molecules being absorbed by the particle surface and surface tension, as a result of capillary action, adhering the particle to a surface.

1.3. Particle attrition

Data indicative of particle de-agglomeration occurring in small scale reverse-flow cyclones for use in dry powder inhaler (DPI) was observed and reported by Cheng [7]. De-agglomeration is a positive feature of a DPI, as this allows the drug to be separated from the carrier powder and efficiently reach the patient's lungs. However this is not so with cyclones that are purely designed for separating dust from an air flow, as particle breakage inevitably increases the number of fine particles which are susceptible to escape, making the cyclone less efficient. Within discussions regarding particle breakage, de-agglomeration refers to the breakage of a particle into similarly sized particles. Whereas attrition may refer to the breakage of a particle into a 'mother' particle and small finer particles, as asperities on the particle surface or sharp corners are broken off through abrasion [29,30], or the breakage of a 'mother' particle into two or three intermediate sized 'daughter' particles [31].

The study of particle attrition within mineral processing cyclones seems to be sadly lacking. As Reppenhagen et al. [32] observed, although literature affords us various cyclone theories, none accounts for the increased quantities of fine particles due to attrition. Reppenhagen commented that this was due to the theories being derived from empirical tests using non-attritable materials, such as quartz. The same is not true of industrial cyclones dedicated to the recovery of catalyst particles used for fluid catalytic cracking (FCC) in oil refineries, where cyclones have been identified as a significant source of particle attrition [29, 32–35]. Unlike solid particulates such as quartz, or indeed the minerals used in this study, catalyst particles are manufactured matrices of clay or gel containing Zeolite and formed by the spray drying of a slurry [33].

Particle attrition in FCC cyclones is due to particle–particle collisions and particle–wall collisions; however FCC cyclones operate under very high solid loadings [19,34] making particle–particle collision more likely than in a lightly loaded cyclone. Therefore it is probable that in a lightly loaded cyclone, which is the focus of this study, particle–wall collisions dominate any attrition process. The operating conditions of a cyclone will affect the readiness of a particle to undergo attrition, as will the material properties, such as its hardness or tenacity. In particular a greater inlet velocity imparts a higher kinetic energy to the particle, increasing the probability of de-agglomeration or attrition resulting from a collision.

Further to Reppenhagen's observation regarding cyclone theories, the authors are not aware of a cyclone model based on mineral processing experiments that addresses attrition, which is included among others [2,36–41]. This may be primarily due to the lack of detailed data in the submicron particle range in grade efficiency studies.

2. Review of experimental results from cyclone research

As mentioned in the Introduction of this paper, there have been several experiments undertaken on cyclones and their separation efficiency of minerals, and all but one have failed to display attrition and many have also been unable to show the occurrence of agglomeration. Several such experiments are reviewed in Sections 2.1 and 2.2, highlighting the different techniques and equipment available to researchers.

2.1. Small scale cyclones

The experimental capabilities and results of five studies of small scale cyclones are briefly reviewed below. In four of the studies neither agglomeration nor attrition was noted by the researchers; however as mentioned previously the study by Cheng [7] was successful in producing results indicative of such particle behaviour.

Kim & Lee [1] carried out separation efficiency studies on a variety of small scale cyclones, with cyclone body diameters of 0.0219, 0.0311 and 0.0411 m. The material type used in the experiments was dioctyl phthalate (DOP), which has a density of 980 kg m^{-3}. The equipment used was a Berglund–Liu aerosol generator (model 3050, TSI Inc., St. Paul, MN) and an aerodynamic particle sizer (model 3300, TSI Inc.), capable of measuring 50 class sizes. Three flow rates of 8.8, 12.4 and 18.4 l min^{-1} were used during the experiments. The research undertaken by Kim & Lee obtained the separation efficiency of particles of size 2–10 μm.

Moore & McFarland [2] undertook separation efficiency experiments with cyclone body diameters of 0.0381, 0.05715 and 0.0889 m. They used both liquid and solid particles in the form of a solution of oleic acid and ethanol tagged with sodium fluorescein for the liquid particles and solutions of ammonia and sodium fluorescein to produce solid ammonium fluorescein particles. A vibrating orifice aerosol generator was used to produce the aerosols for both the liquid and solid particles. The collection efficiency of the cyclone was calculated by taking samples of particle deposition from five different areas in the cyclone. The particles were sized using a light microscope, with concentrations being ascertained by calculating the relative fluorescein concentration in the aerosol that was collected on filters upstream and downstream of the