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Pumice attrition in an air-jet

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ABSTRACT

We present the results from a series of jet-attrition experiments performed using a standard ASTM device (ASTM D5757-00) on naturally occurring ash-sized (<2 mm) pumice, a product of explosive volcanic eruption comprising highly porous silicate glass. We investigate the effect of both feed grain size and attrition duration on the production of fines. We utilize a wet methodology for fines collection to ensure recovery of the total grain size distribution for each experimental run. The experiments convert a restricted size range of pumice particles to a bimodal population of parent and daughter particles. The bimodal distribution develops even after short (~15 min) attrition times. With increased attrition time, the volume of daughter particles increases and the mode migrates to finer grain sizes. Jet attrition efficiency depends heavily on the particle size of the feed; our data show little attrition for a feed of 500 μm vs. highly efficient attrition for a 250 μm feed. Our rates of attrition for pumice are extremely high compared to rates recovered from experiments on limestone pellets. Fines production data are well modeled by:

$$\frac{m_{fines}}{m^0_{bed}} = 0.291\left(1-e^{-0.312t}\right)$$

where m^0_{bed} is the initial mass of particles in the bed, t is in hours, and the two adjustable coefficients dictate the long time limiting behaviour (0.291) and the rate at which the limit is reached (−0.312). This functional form provides more realistic limits in time while preserving a zero intercept and defining a plateau for long residence times.

1. Introduction

Particle attrition is a process that operates in a diverse range of engineering and natural environments to cause particle size reduction, as well as, reshaping and resurfacing of particles. In the engineering sciences, particle attrition studies are commonly experimental in nature and concern the mechanisms, rates, and consequences of attrition in fluidized and conveyed systems. The experiments involve diverse materials such as: fluid cracking catalysts [1], limestone particles [2], and CO_2 sorbent pellets [3,4], tested under conditions relevant to the engineering environment. Attrition is also widespread in geological processes including sediment transport (e.g., stream beds, beach sand), volcanic eruption (e.g., xenolith milling), and glaciation (e.g., till deposits). There are, however, few experimental studies of attrition in geologically relevant systems or on geological materials. Exceptions include, but are not limited to: secondary fragmentation of crystal rich ash [5]; rounding of pumice clasts during transport in pyroclastic density currents [6]; wear of kimberlitic minerals [7–10]; milling of lithic material within volcanic conduits [11] and abrasion of geological materials by eolian action [12].

Pumice is a naturally occurring resource produced through explosive volcanic eruptions. It is commonly defined as a highly vesicular silicic to mafic glass foam, having a bulk density less than water (i.e. floatable) [13,14]. Pumice represents an interesting material because it has unique properties: high vesicularity, low density, and a contiguous glass (i.e. not crystalline) framework. This porous volcanic material is of interest to both engineering and geological sciences. Some existing uses of pumice in industry include: a natural pozzolan for cement [15]; abrasives in skin products and dentistry; water filtration [16]; a chemical or catalyst carrier in fluidization systems [17,18] and as an inert fluidizing solid [19]. These latter applications are of particular relevance to this study; if pumice is to be used in a fluidized system it is important to understand how grain size may evolve with residence time in the fluidized apparatus. On its own, pumice has low strength due to its highly vesicular nature and is easily broken down by crushing and fracturing of the thin, typically interconnected, glass bubble walls. Its low density has made

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it an ideal aggregate in cement to reduce the density of concrete; it does so without reducing the strength of the concrete significantly.

Yet, despite its widespread industrial uses and its importance in geology, its susceptibility to attrition remains poorly known [20]. Pumice attrition has rarely been studied experimentally. Previous experimental work on pumice has shown the grain size reduction of pumice by ball milling [21–23] and the decrease in fines production with increased milling duration by rock tumbling [6,24]. These experiments inform on attrition processes typically involving continual particle-particle contact whereas air-jet experiments feature much shorter durations of particle-particle contact. A small amount of experimental work involving fluidization of pumice [25,26] has been done in volcanology with the aim of understanding: grain size distributions and sorting within natural deposits; the degree of particle segregation during flow; and elutriation of fine particles produced by attrition.

Here we present a suite of attrition experiments involving particles of pumice within an ASTM standard device providing a particle-laden jet. Our experiments are designed to further our understanding of how pumice (i.e. porous glassy material) undergoes grain size reduction in a gas jet and have relevance to fluidized beds using pumice as a catalyst support [27–29]. The experiments use well-characterized pumice particles having a known initial total grain size distributions (TGSDs) and bed mass are subjected to jet attrition for fixed amounts of time. We then collect the experimental run-products and process them for their TGSD and use the data to establish rates/mechanisms for pumice attrition and the evolution of grain size with residence time.

2. Review of attrition in a gas jet

Attrition processes comprise two primary mechanisms of particle size reduction: fragmentation and abrasion. Fragmentation refers to particle fracturing wherein the original particles (i.e. parent or mother particles), subjected to critical collisions are mechanically broken into smaller particles (i.e. daughter particles). Collisions causing fragmentation typically result from direct impact with other particles or a hard surface at, or above, a critical threshold velocity. Commonly the parent particle is fragmented into a number of smaller particles of similar size. Attrition by abrasion is a less energetic mechanism involving wearing or rounding the rough edges or asperities of mother and daughter particles via lower energy particle-particle impacts. Abrasion generates a significant number of very fine particles, leading to bimodal grain size distributions, and creates particles with smoother morphologies.

Several factors govern the mechanisms and efficiency of attrition in fluidized gas-solid systems. The environmental factors, or experimental controls, include residence time in the attrition jet, temperature, gas type, vessel pressure, bed load and gas velocity. The important material properties governing attrition include grain size, hardness or strength, density, particle shape and surface texture [1].

Gwyn [30] was one of the first to study and model the production of fines in a fluidized system by attrition. His attrition experiments showed the production of fines to vary non-linearly with time (t) and he modelled the fines production as:

$$\frac{m_{fines}}{m^0_{bed}} = K_a t^b \tag{1}$$

where m_{fines} and $m^0{}_{bed}$ are the mass of fines and the initial bed particles, respectively [30]. The parameters K_a and b are constants determined by fitting Eq. (1) to experimental data. Commonly the experimental data show a dramatic and rapid decay in attrition rate after a brief period of initial attrition where the rough edges of the original particles are broken off to form smoother surfaces [30]. This empirical equation captures this behaviour well and the Gwyn model has been used extensively to describe many different experimental datasets. However, one recognized limitation of Eq. (1) is that it assumes that all collisions are below a threshold velocity that would cause particle fracturing, creating new rough fracture edges [4]. Subsequent extensions of the Gwyn model focused on the three main areas of fluidized systems where attrition can occur: jet attrition [31]; bed and bubble attrition [32] and cyclone attrition [33].

In this study, we focus on jet attrition, the dominant mechanism operating within our experimental set-up (Fig. 1; [2,4,34]). When jet attrition is the dominant process, the mass of fines produced through time can be modeled as:

$$m_{jetfines} = C_{jet} d_{pb} n_{or} \rho_g d^2_{or} u^2_{or} \tag{2}$$

where C_{jet} is a fitted constant, d_{pd} is the bed particle diameter, n_{or} is the number of orifices, ρ_g is the fluidizing gas density, d_{or} is the orifice diameter and u_{or} is the gas velocity at the orifice. Alternatively, the attrition rate can be modeled with the mean particle diameter. This is less common, due to the extra work needed to characterize the particle size distribution (PSD), however it enables a complete understanding of the attrition processes (abrasion vs. fragmentation) operating.

3. Methodology

3.1. Pumice samples from Mount Meager, British Columbia

The Mount Meager volcanic complex is a calc-alkaline stratovolcano complex situated approximately 150 km north of the city of Vancouver, in southwestern British Columbia and belongs to the northernmost extension of the Cascade Volcanic Arc [35]. The most recent eruption of the Mount Meager is dated to 2360 BP [36] and produced explosive and effusive dacite volcanic deposits including: pyroclastic fall deposits, pyroclastic flow deposits, and lava [37]. For this study, blocks (>10 cm) of pumice were collected from proximal to medial outcroppings of the pyroclastic fall deposit. The fallout deposit (Pebble Creek Formation of [35]) varies in thickness from 1 m to >60 m near the volcanic vent,

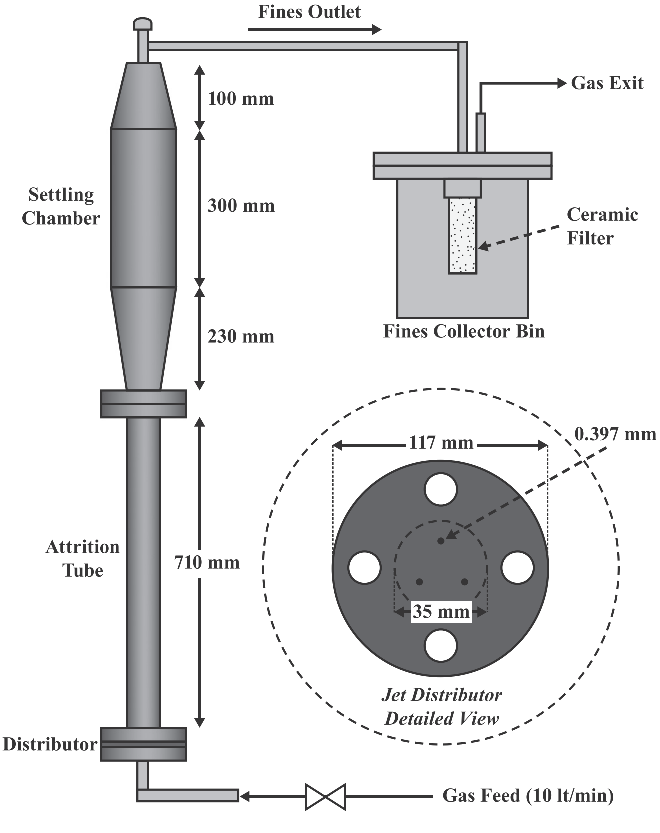

Fig. 1. Schematic representation of standard ASTM experimental apparatus (ASTM D5757-00) used for jet attrition experiments (modified from [4]).