

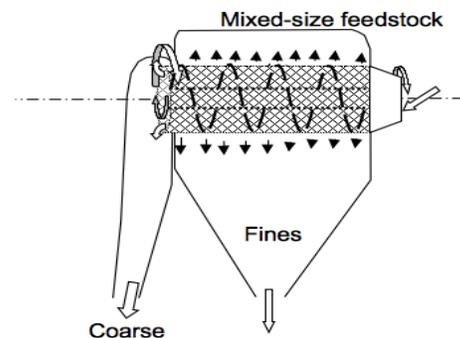
## SUPLANTING GRAVITY WITH CENTRIFUGAL FORCE FOR SIEVING AND PROCESSING

**REGOLITH UNDER MICRO-GRAVITY** C. B. Dreyer<sup>1</sup>, O. Walton<sup>2</sup>, and E. P. Riedel<sup>3</sup>, <sup>1</sup> Colorado School of Mines, Department of Mechanical Engineering, 1600 Illinois St, Golden CO 80401; Ph (303) 273-3890; email: [cdreyer@mines.edu](mailto:cdreyer@mines.edu); <sup>2</sup> Grainflow Dynamics, Inc., 1141 Catalina Drive, PMB 270, Livermore, CA 94550-5928; Ph (925) 447-4293; email: [walton@grainflow.com](mailto:walton@grainflow.com); <sup>3</sup> Ned Riedel Engineering, LLC, 150 South 31st Street, Boulder, CO 80305, (720) 596-4820; email: [ned@riedel-eng.com](mailto:ned@riedel-eng.com)

**Introduction:** In any microgravity environment movement and/or processing of regolith will have to rely on means other than gravity flow. Under any reduced gravity conditions, such as a lunar environment, the cohesion of fine granular materials will make handling and processing operations that utilize gravity function significantly different from similar operations under terrestrial conditions. Minimum openings of gravity-flow hoppers will need to be much larger [1], vibrational sieving will not function well for the smallest sizes [2], the effective Geldart classification of powders for fluidization [3] will be shifted so that larger-size powders are considered to be category C, cohesive-powder. Many of these issues can be addressed through the use of mechanical or pneumatic conveying for transport of regolith, and through the utilization of centrifugal force in processes, such as sieving and fluidized beds, that depend on a body force for part of their function. A centrifugal-sieve separator can provide efficient gravity-level-independent size classification of granular feedstock, like lunar regolith, utilizing centrifugal force as the primary body-force, combined with shearing flow and vibratory motion. A prototype centrifuging sieve demonstrated the ability of a rotating cylindrical screen with induced axial flow of regolith on the inside to separate size fractions of JSC-1a lunar simulant. The cylindrical screen separates particles, with the fines passing through the outer wall screen, and the coarse material passing axially through the continuous feed system. The prototype was designed for semi-autonomous operation during reduced-gravity flights, and/or under vacuum conditions, and other concept designs which are fully micro-gravity compatible, utilizing no gravity-flow components for feeding or extracting regolith size fractions, have been developed.

**Centrifugal Sieve Concept:** Terrestrial size separation methods for dry materials often depend on gravity. For very fine particulates, the gravity-force is often supplemented with either vibration or forced shearing over a sieving screen. Centrifugal sieves can likewise utilize either vibration or shearing flow to enhance separation. When vibratory and mechanical blade sieving screens designed for terrestrial conditions were tested under lunar-gravity [2], they did not function well. Utilizing centrifugal force as the primary body-force, combined with shearing flow and vibratory motion, the centrifugal-sieve separator can

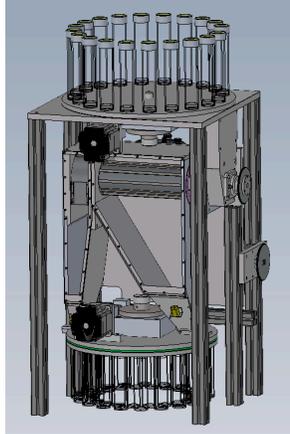
provide efficient gravity-level-independent size classification of granular feedstock like lunar regolith. The centrifugal-sieve can operate in low-gravity (1/6-g and 3/8-g) and micro-gravity as well as utilize multiple feedstock sources. Granular materials naturally stratify during shear-flow with larger particles rising to the top. The centrifugal sieve size-separator utilizes the natural size stratification of flowing granular solids. A schematic of the concept is shown in Figure 1. Material enters from the right into a rotating cylindrical screen. A helix/screw inside the screen rotates at a slightly greater rate, to shear the material bed and move it to the output end. Fines are forced through the screen by centrifugal force. Coarse material is moved to the end and leaves the screen.



**Figure 1.** Schematic of centrifugal sieve concept

**Microgravity Test Apparatus:** A test apparatus using a size-separating screen at the outside of the flow to separate particles, with the fines passing through the outer wall screen, and the coarse material passing axially through the continuous feed system was built for use on NASA micro-gravity aircraft (Figure 2). The test apparatus is designed for semi-autonomous operation during reduced-gravity flights, and/or under vacuum conditions. A carousel of test-sample aliquots provides up to 20 pre-measured quantities of regolith simulant (~200g) to the centrifuging sieve. Testing of multiple operating conditions without opening an outer containment shroud is possible with this system. Two separate output-stream receptacle carousels of 20 containers each collect the fine and coarse material from each discrete-operating-condition test. Sieving performance in size distribution and mass delivered to the two output streams can be determined in post-flight analysis.

Operating at a centrifugal g-level of 1.5g on the screen wall in gravity, the centrifugal sieve was able to separate coarse oversize material (larger than 5mm diameter) from lunar regolith simulant JSC-1A, and to separate the size fraction of JSC-1A smaller than 100-microns from the material larger than that cutoff size (Figure 3). The rotational speed of the screen was 188 rpm and the auger/brush was 60 rpm greater. The 100  $\mu$ m screen achieved roughly 50% of the material being separated into each receiver bin (Figure 4).



**Figure 2.** Centrifugal sieve micro-gravity aircraft flight test apparatus



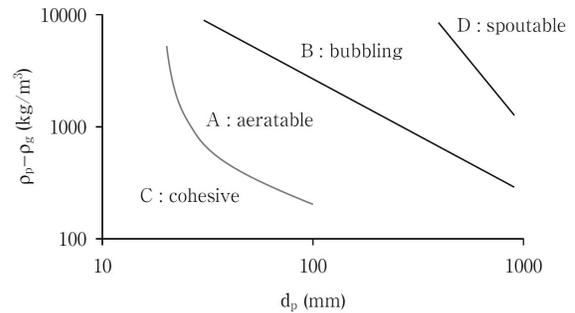
**Figure 3.** Centrifugal sieve ground testing. Left: 4.6 mm screen. Right: 100  $\mu$ m screen, top video still, bottom post test.



**Figure 4.** Sieved 100  $\mu$ m JSC-1a. Left oversize, right fines which passed through a 100  $\mu$ m screen.

**Fluid Bed Processing** – A common mode of processing granular solids is in fluidized bed, and they are also under consideration for a various resource recovery processes on the moon. Powders are typically categorized for fluidization according to the Geldart [3]

classification as: C – cohesive (very fine), A – aeratable (non-bubbling, uniform fluidization w/air under ambient conditions), B – bubbling fluidization, D – spouting bed (large particles) see Figure 5.



**Figure 5** Geldart [3] classification of powder fluidization properties, by size and density.

Qian et al [4] examined the effects of the body-forces acting on particles in fluidized beds through the use of a rotating cylindrical chamber with a porous frit on the outer wall, so that fluidizing gas traveled from the outer radius to the center region of the rapidly rotating (centrifuging) cylindrical fluidized bed. Williams et al. [5] examined an extrapolation of Qian et al’s relationship in the opposite direction, by looking at fluidization of glass and alumina powders under *reduced* gravity conditions (during parabolic flights). They found that the boundaries of Geldart classification changed with g-level such that that a given powder will behave more cohesively in a fluidized bed at reduced gravity than it does under terrestrial fluidization. Suplanting gravity with centrifugal force, after Qian et al [4] allows more cohesive powders to successfully fluidized – offering a solution for fluidized bed processing under reduced gravity conditions.

**Conclusions:** The feasibility of utilizing centrifugal force as the primary body-force for sieving granular feedstock like Martian, Lunar or Phobos regolith was demonstrated. The approach of a centrifugal sieve can provide efficient gravity-level-independent size classification of granular feedstock. Centrifugal force can, likewise, supplant gravity in other body-force dependent regolith processing operations, like fluidized beds.

**References:** [1] Walton (2012) in *Moon: Prospective Energy and Material Resources*, ed. Badescu, Springer-Verlag, [2] Ramé, et al. (2010), Zero-G Aug 13-14, 2009 Flight Final Report, NASA-GRC, [3] Geldart, D. (1973) *Powder Technology* 7:285-292 [4] Qian et al (2001) *AIChE Journal*, 47(5) p1022-1034, [5] Williams et al (2006) *Granular Matter*, 10(2), 139-144.