CENTRIFUGING-PIPE CONVEYOR FOR REGOLITH. O. R. Walton[1], C. B. Dreyer[2], and A. I. Abdel-Hadi[3], [1]Grainflow Dynamics, Inc. 1141 Catalina Drive, PMB 270, Livermore CA 94550 (walton@grainflow.com), [2]Division of Engineering, Colorado School of Mines, Golden, CO 80401 (cdreyer@mines.edu), [3]Aerospace Sci. Eng., Tuskegee University, 100 Luther Foster Drive, Tuskegee, AL 36088 (ali.Abdel-Hadi@tuskegee.edu)

Introduction: ISRU operations will need a robust, method of transporting loose regolith over short distances and up to the top of processing units. With the simplicity of an ordinary screw conveyor (e.g., a single moving part) a new centrifuging-pipe conveyor can transport cohesive powders at any inclination, independent of prevailing gravity level.

Background: Many granular solids conveying methods depend on gravity for at least a portion of their motive force. Under lunar gravity they may be less reliable than under terrestrial conditions [1]. Almost all plans for extended lunar operations include the production of oxygen from lunar regolith, but even shorter missions will involve collection, moving, handling, and often processing of fine cohesive regolith powder. The excavation rate needed for O_2 production is on the order of 50kg/hr and for site-preparation tasks up to 300 kg/hr would need to be excavated and moved. NASA needs hardware that is able to operate over broad temperature ranges (40 K to 400 K) and in the presence of abrasive lunar regolith and partial-gravity environments. Generally NASA needs lunar regolith handling hardware that is robust, lightweight, abrasion resistant, made from vacuum- and large-temperature-variation-compatible materials, and with low power, low maintenance, and has a minimum of dust generation during operation. The centrifuging-pipe conveyor described here is being developed to meet those needs.

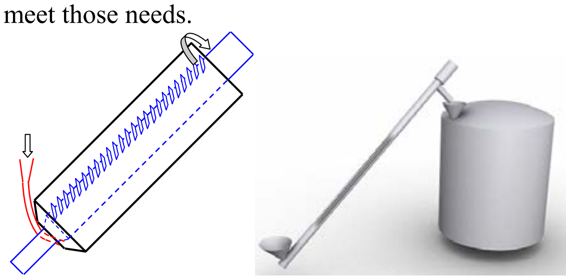


Figure 1. Schematic of centrifuging-pipe conveyor

Centrifuging-pipe concept: The proposed centrifuging step-screw conveyor uses a novel mode of solids transport wherein the regolith spends most of its time, centrifuged to the inner wall of a rotating pipe with no relative motion between the regolith and the pipe wall. Once per revolution the material on the wall encounters a stationary angled blade or 'screw-step' which displaces the material a short distance axially along the rotating pipe wall. If the pipe is oriented horizontally the screw-step is ideally located at an angular location which is just after the material has passed the top of the rotating pipe. At this point the normal force is lowest (a small fraction of the normal weight of the material) so it is very easy to shear and deflect it in the axial direction. After encountering the short step-screw blade, gravity assists in accelerating the regolith to recover part of the circumferential velocity component lost when it was deflected axially. In inclined transport, the diverting screw-steps are still most efficient when located circumferentially just after the material has passed its highest point in its circumferential path moving with the rotating pipe wall. For purely vertical (upward or downward) transport there is no preferred circumferential location for the step-screw blades. In between the diverting steps, the material rotating with the pipe wall, is held in place by a combination of centrifugal force, frictional forces within the regolith bed, and frictional forces on the pipe wall. Axial motion only occurs in distinct steps, once per revolution, as the centrifuged regolith encounters the screw-steps (see Figs 1 and 2).

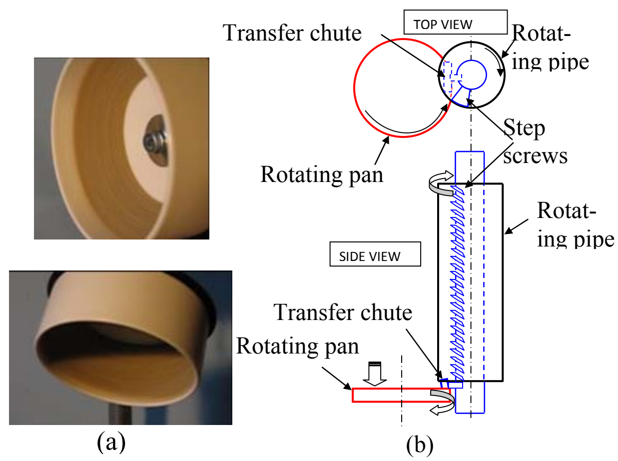


Figure 2 (a) sand centrifuged on the walls of rotating cylinders, (b) schematic of a vertical implementation of a centrifuging-pipe conveyor, with separate 'acceleration pan'.

Theoretical analyses and numerical simulations of granular material centrifuging on the inner walls of rotated horizontal and vertical cylinders [2, 3] showed that in order for a granular material to remain stationary on the inner wall of a rapidly rotating vertical pipe, the rate of rotation must be sufficient for the following two inequalities to both be satisfied,

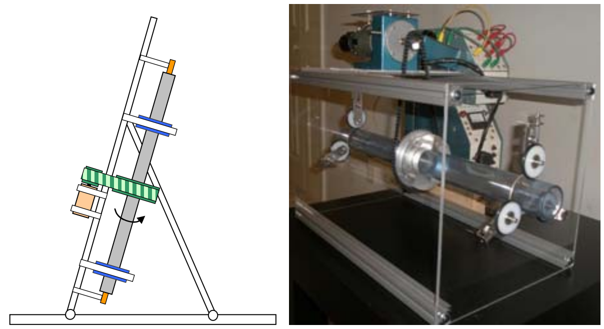
$$\frac{\omega_p^2 R_i}{g} > \frac{1}{\tan\phi_r}, \qquad \text{and} \qquad \frac{\omega_p^2 R_i}{g} > \frac{1}{\tan\phi_w},$$

where ω_p is the angular rotation rate (*rad/s*) of the pipe, R_i is the inner radius of the granular layer on the inside of the rotating pipe, g is the acceleration of gravity, ϕ_w is the wall friction angle between the pipe wall and the granular solid (*i.e.*, the arctangent of the wall friction coefficient), and ϕ_r is the angle of repose of the granular material. For horizontal pipes, similar relations are obtained, except that $\sin\phi$ replaces $\tan\phi$.

For typical material and wall properties this means that a horizontal pipe needs to rotate nearly 50% faster than enough for the centrifugal force to just balance gravity at the inner surface of the granular material at the top of the cylinder in order to prevent any circumferential sliding or shearing of the rotating granular layer on the wall of the pipe. At slower rotation rates, gravity tends to cause a slight slowing (and shearing deformation) of the 'rising' material and a slight acceleration of the 'falling' material, at circumferential locations that would correspond to about the 10:30 o'clock and 1:30 o'clock positions (assuming an analog clock face is oriented perpendicular to the pipe's axis).

Material being centrifuged on the inner wall of the conveying pipe of this design have circumferential velocities of at least 0.65m/s (for 5cm diameter pipes), or 1.13m/s (for 15cm diameter pipes) under terrestrial conditions. For lunar applications the velocities are about a factor 0.4 lower. This circumferential velocity represents the speed at which the material encounters the stationary deflecting step screws. The inertia of the granular material, at these velocities, will overcome weak cohesive forces in the material and allow the material to deform and move in response to the 'encounter' with the stationary screw steps. Since the rate of rotation is not limited to the minimum speed that would allow this technique to function, the standard operating rotation rate of the outer pipe can be increased significantly to overcome the cohesive effects of 'difficult' materials. To achieve typically required non-dimensional rotation rates with $\omega_p^2 R_i/g = 2$, (*i.e.*, $\omega = \sqrt{2}\,[g/R]$), on a $5cm$ inner radius pipe under lunar conditions, the rotation rate would need to be on the order of 65RPM. Conventional terrestrial screw conveyors, in totally enclosed tubes, often operate with screw rotation rates 3 or 4 times this high [4].

At the exit of the step-screw conveyor, the placement of the last step-screw blade will determine the direction that the granular material will travel upon exiting the conveyor with a combined axial and tangential velocity trajectory. That exiting material can be directed, via curved chutes, onto the inner wall of any succeeding step-screw module, oriented in any direction – even straight up. Thus, successive units can be daisy-chained together to form almost any arbitrary conveying path, with abrupt changes in direction at each junction point.



(a) (b)

Figure 3 (a) Schematic of belt-driven and, ball-bearing supported unit under construction in Colorado, (b)Snapshot of chain-driven, wheel-supported unit at Tuskegee University.

(a) (b)

Figure 4 (a) Blades being aligned on a machinists flat, and (b)Blades inside of prototype centrifuging pipe conveyor under construction at Tuskegee.

Figures 3 and 4 show schematics and snapshots of prototype bench top units being built, to test the conveying concept and optimize design parameters.

Concluding Remarks: A centrifuging-pipe conveyor can provide a robust, low-dust method of transporting loose regolith over short distances (up to several meters) at any inclination angle. The design has low frictional losses compared to conventional screw conveyors, and modules can be daisy-chained together, with abupt angle changes, up to 180°, at each transition. Demonstration units are being fabricated.

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