Experimental Testing and Modeling of a Pneumatic Regolith Delivery System for ISRU

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Excavating and transporting planetary regolith are examples of surface activities that may occur during a future space exploration mission to a planetary body. Regolith, whether it is collected on the Moon, Mars or even an asteroid, consists of granular minerals, some of which have been identified to be viable resources that can be mined and processed chemically to extract useful by-products, such as oxygen, water, and various metals and metal alloys. Even the depleted "waste" material from such chemical processes may be utilized later in the construction of landing pads and protective structures at the site of a planetary base.

One reason for excavating and conveying planetary regolith is to deliver raw regolith material to in-situ resource utilization (ISRU) systems. The goal of ISRU is to provide expendable supplies and materials at the planetary destination, if possible. An in-situ capability of producing mission-critical substances such as oxygen will help to extend the mission and its success, and will greatly lower the overall cost of a mission by either eliminating, or significantly reducing, the need to transport the same expendable materials from the Earth.

In order to support the goals and objectives of present and future ISRU projects, NASA seeks technology advancements in the areas of regolith conveying. Such systems must be effective, efficient and provide reliable performance over long durations while being exposed to the harsh environments found on planetary surfaces. These conditions include contact with very abrasive regolith particulates, exposure to high vacuum or dry (partial) atmospheres, wide variations in temperature, reduced gravity, and exposure to space radiation. Regolith conveying techniques that combine reduced failure modes and low energy consumption with high material transfer rates will provide significant value for future space exploration missions to the surfaces of the moon, Mars and asteroids. Pneumatic regolith conveying has demonstrated itself to be a viable delivery system through testing under terrestrial and reduced gravity conditions in recent years.

Modeling and experimental testing have been conducted at NASA Kennedy Space Center to study and advance pneumatic planetary regolith delivery systems in support of NASA's ISRU project. The goal of this work is to use the model to predict solid-gas flow patterns in reduced gravity environments for ISRU

Modeling Approach: In recent years, one step forward in the physical understanding of gas-solid systems has been taken by the development of kinetic theory for two-phase flows based on the theory for non-uniform gases. The kinetic-theory approach has been applied to model and simulate the mixing of the gas (air) and the solid (regolith) at the eductor and the subsequent two-phase flow formation and the pneumatic transportation of the regolith. Model results are able to describe the main features of the gas-solid flow, such as granular temperature, solid pressure viscosity, gas pressure drop, oscillation frequency, core-annular flow regime, and transient behavior of the flow. Granular temperature, a key feature of kinetic-theory, is a measure of the velocity fluctuations in a fluidized granular system (known as a granular gas) and can be found either by detailed measurements of the grains' velocities, numerically (in simulations) or experimentally.

The dependent variables for each of the two phases are: phase fraction (expressed as volumetric fraction), velocity, pressure, stress tensor, and granular temperature. Two gas pressure values, one inside the regolith supply hopper and the other at the eductor's gas inlet are assumed to be constant and set as boundary conditions in the model. Since it was observed experimentally that the gas flow at the eductor inlet gas line is not constant, the model assumes that a large buffer tank filled with gas is connected to the eductor

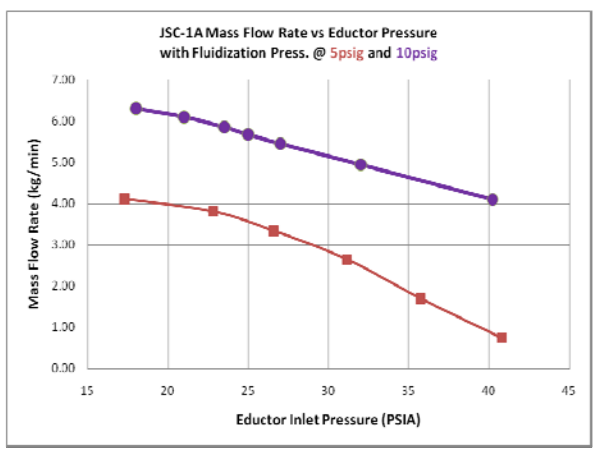

Figure 1. Experimental results for the eductor mass flow rate for two different fluidization pressures

inlet gas line allowing the eductor inlet gas flow to vary and depend on the flow pattern developed at the eductor as inferred by the experimental observations.

Experimental Setup: The experimental setup consists of a cylindrical hopper vertically connected to an eductor; an inlet gas line is connected to the eductor and an additional independent gas line is connected to the hopper to keep the regolith particles fluidized. The eductor outlet line is open to the ambient environment. The entire setup stands on a large digital mass scale to record the transient mass loss as the eductor mixes the gas entering its inlet gas line with the regolith particles coming from the hopper and transport them along the eductor outlet line as a dense solid-gas phase flow toward the open end.

Experimental Results: Experiments were conducted under terrestrial and reduced gravity testing conditions with our pneumatic regolith feed system using dry air and helium as convey gases, and the planetary regolith simulants JSC-1A, NU-LHT-2M, and Tephra.

Figure 1 summarizes the experimental results obtained with our pneumatic regolith delivery system under terrestrial gravity laboratory conditions at NASA Kennedy Space Center using compressed dry air as the convey gas. As indicated in Fig. 1, the regolith mass flow rate decreases with increasing applied gas pressure at the inlet for two different inlet pressures at the hopper, 10 and 5 psig.

Model Predictions: The solid-gas flow model implemented in this work is based on kinetic theory; a straightforward approach on the boundary conditions was used assuming that the flow rate and pressure at the eductor inlet gas line are constant and also that the pressures in the hopper and the eductor are always the same. Figure 2 illustrates the model settings for the 2D geometry and boundary conditions. Dimensions of the actual eductor used in the experimental unit were measured and utilized in the transient 2D solid-gas flow model as illustrated in Fig. 2. As the regolith particles flow is not evenly distributed across the pipe, the particle flow rate is computed by integrating the particle flow rate along the pipe diameter. Fig. 2 also shows a snapshot of mass solid fraction distribution using the model setting originally assumed; Figure 3 depicts the relation between regolith mass flow and eductor mass flow predicted by the model under these straightforward approach settings.

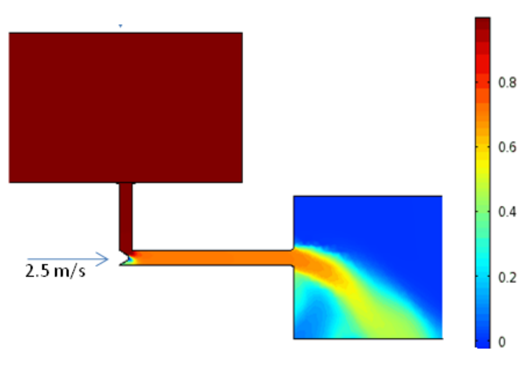

Figure 2. Initial model boundary conditions and particle mass fraction distribution predicted by the model for an inlet gas flow of 2.5 m/s

As illustrated in Fig. 3, the model agrees with the trend

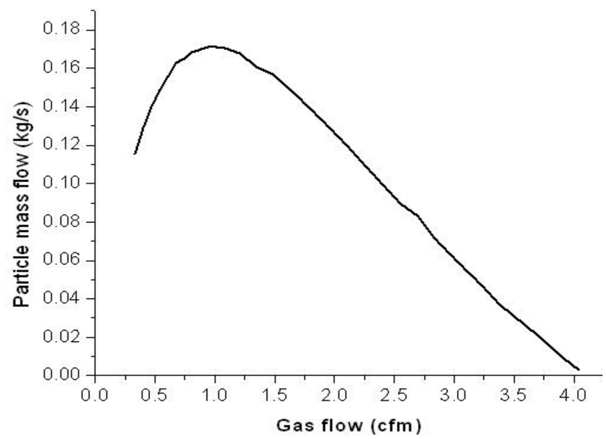

Figure 3. Model Prediction for constant inlet flow and hopper pressure equal to eductor inlet line pressure.

found experimentally, a decrement on regolith mass flow as the eductor pressure (proportional to the mass flow) increases. The model predicts a maximum regolith mass flow (see Fig 3) as the regolith mass flow reaches its maximum potential and starts decreasing as the eductor inlet flow keeps decreasing and approaching to zero. Experimental testing at lower eductor flow rates need to be performed to validate the model prediction.

Since boundary conditions for the experimental results shown in Fig. 1 happened to be different than those originally used in the model (Fig. 2), the model needs to be upgraded to use more realistic boundary conditions and be able to predict the regolith mass flow values found during the experimental tests. The boundary conditions found in the experimental testing do not allow the assumption of constant eductor flow rate as originally assumed. A large buffer tank filled with gas and connected to the eductor will replace the boundary that assumed constant eductor inlet flow rate.