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

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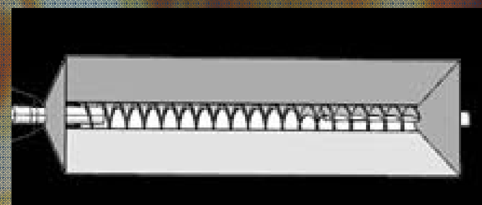
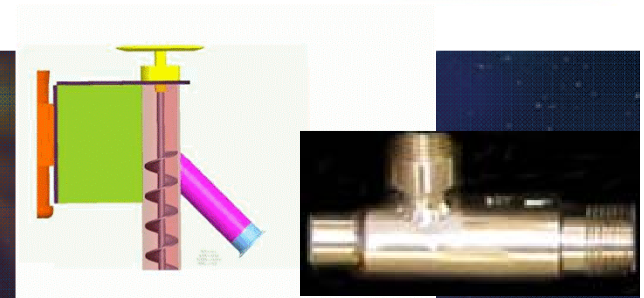
Outline

- Regolith Feed Systems:
  - Auger
  - Pneumatic
- CFD-based model
- Experimental & Model Results
- Introduction of Kinetics-based model

Excavation and Delivery of Planetary Regolith for ISRU Systems





Excavator Delivers Regolith to Trough

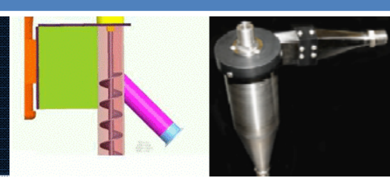
Regolith is Transferred from the Trough to Regolith Supply Bin

Regolith is Conveyed to an ISRU Reactor

Regolith is Chemically Reacted to Yield Useful Products Like Oxygen and Metals such as Titanium

E.g., Carbothermal, Hydrogen Reduction, Molten Oxide Electrolysis

Spent Regolith is Conveyed out of the ISRU Reactor



ISRU Regolith Feed System Evolution

Mechanical
(Inclined Auger)


ROxygen I


PILOT

Non-mechanical
(Pneumatic Conveyor)


RGF Test Unit


Field Demo Unit

Comparison of Regolith Delivery Systems

Mechanical (Inclined Auger)

Pros

- Simple
- More experience
- Can be design to be very robust

Cons

- Moving parts ->Wear concerns
- Reconfiguration and Sprawl
- Jamming concern
- Power and cooling of motor

Non-mechanical (Pneumatic Conveyor)

Pros

- Compact
- Improved performance in 1/6 g
- System commonality – reuse of ISRU fluidization components

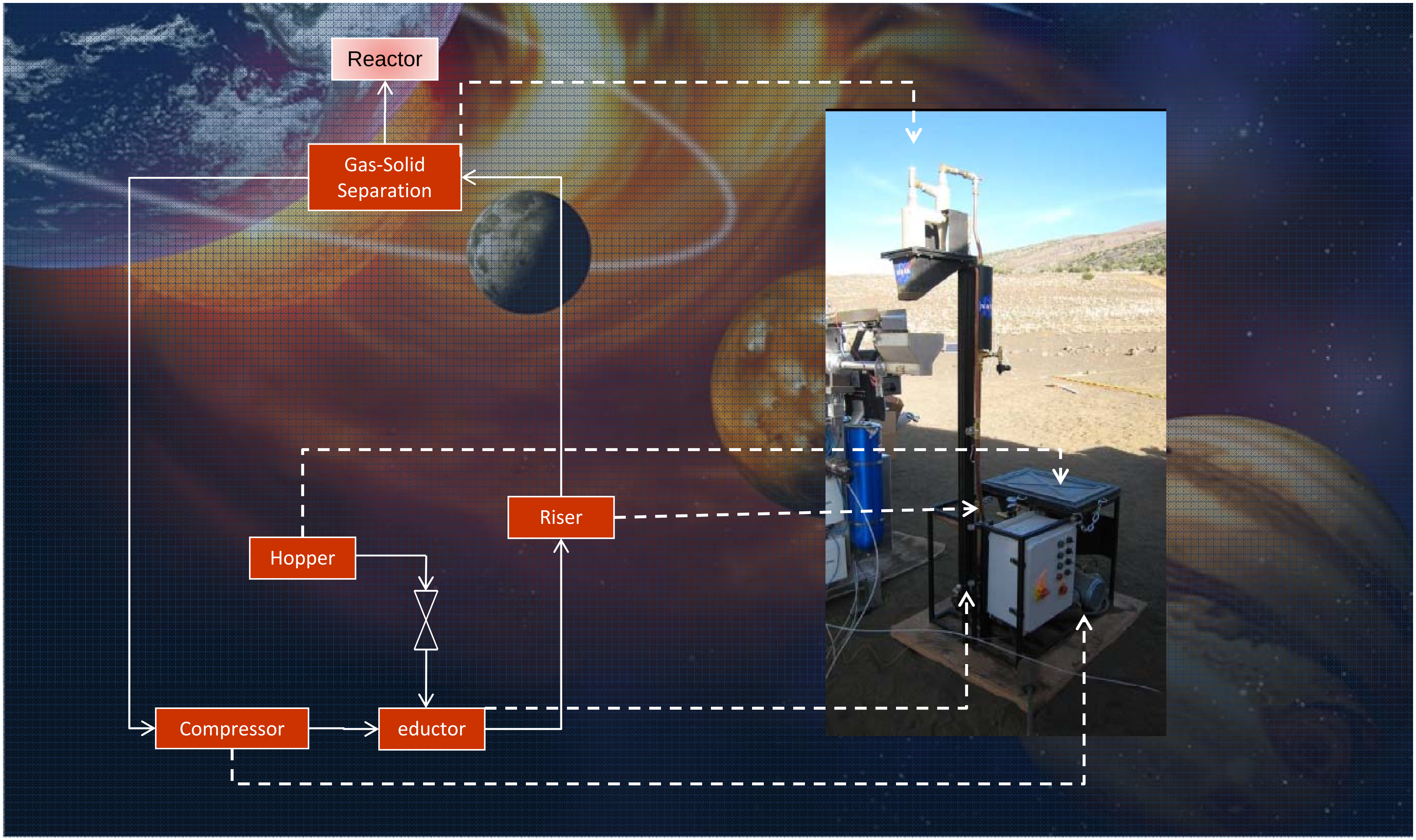
Cons

- Complexity
- Cooling of regolith
- Wear due to sandblasting
- Requires size sorting
- Compressor is required if not already used by ISRU system

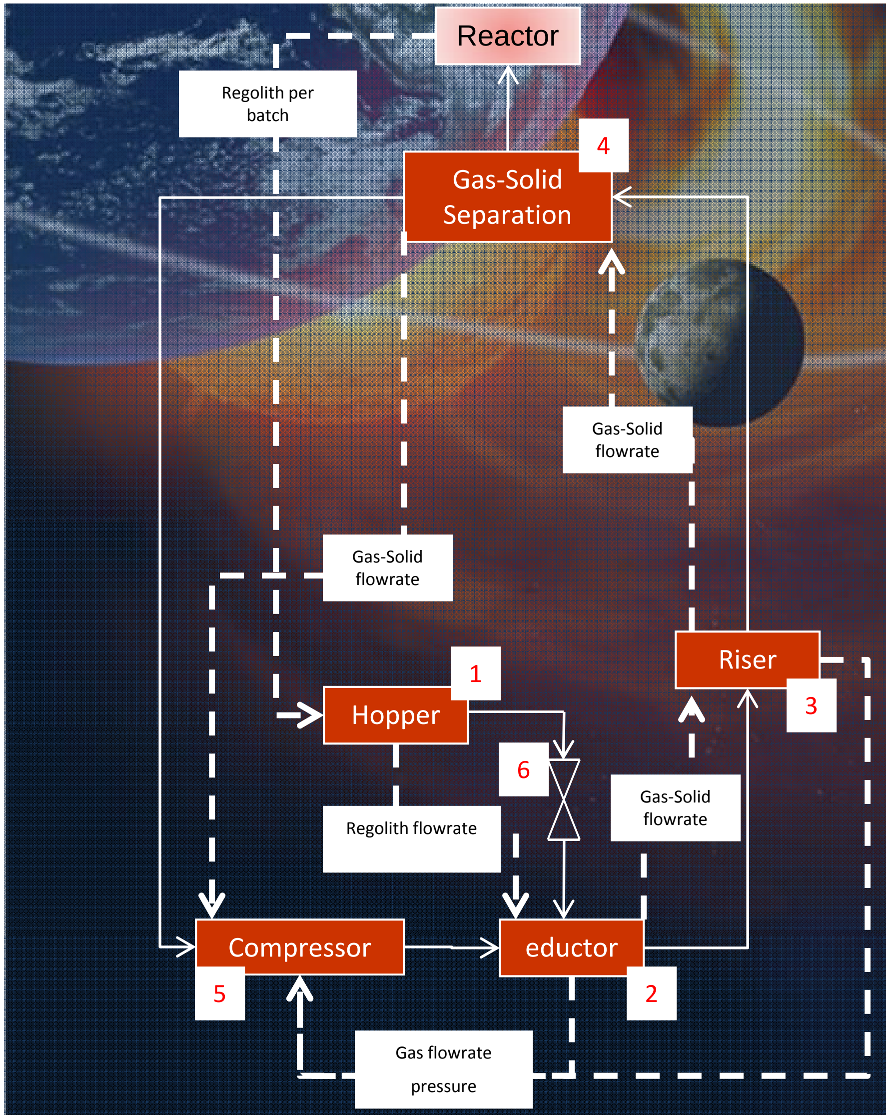
Regolith Feed System Model

- The use of analytical model provide a unique opportunity to perform parametric analysis of the system's performance
- When combined with experimental data, analytical model are a powerful tool to understand the system behavior
- The ISRU modeling tool currently includes an auger-based feed system.
- Pneumatic feed system analysis and model have been missing from the ISRU Model Tool

Pneumatic Regolith Feed System – Model Architeture



Pneumatic Regolith Feed System Model Description & Sequence



1. Hopper:
   - Mechanical model based on Static Forces of regolith given a regolith per batch requirement and buffer time
   - GRC-developed model
   - Sized based on regolith batch size from reduction reactor
2. Venturi Eductor:
   - Solid-gas flow model based on mass and momentum balance
   - Given batch size and time to transfer the solids, it calculates solid and gas flow rate required
3. Riser:
   - Solid-gas flow model based on mass and momentum balance
   - Given the gas and solid flow rate calculated from eductor model, it calculated conduit requirements
   - Verifies gas and solid flow rates from eductor
4. Gas-Solid Separation:
   - Model based on cyclone and particulate filter to remove solids from gas
   - GRC-developed cyclone model
   - Given gas and solid flow rates (from eductor or adjusted from riser model), it calculates cyclone dimensions
5. Compressor:
   - Model compressor from manufacturer performance curves based on eductor requirement for gas flow and delta-P.
   - Compares eductor and riser gas flow and pressure requirements, uses highest requirements to size compressor
6. Valve:
   - Use manufacturer specifications
   - Given gas pressure and solid flow rate, it calculate valves dimensions and requirements.

TWO-PHASE FLOW MODELING: GAS AND DILUTE SUSPENSION FORMED BY PARTICLES

Mass Balance

$$\frac{\partial \phi_s}{\partial t} + \nabla \cdot (\phi_s \mathbf{u}_s) = 0$$

Solid mass balance

$$(\rho_f - \rho_s)[\nabla \cdot (\phi_s (1 - c_s) \mathbf{u}_{slip})] + \rho_f (\nabla \cdot \mathbf{u}) = 0$$

$$\mathbf{u}_{slip} = \frac{\mathbf{J}_s}{\rho_s \phi_s (1 - c_s)}$$

Continuity balance

$$\frac{\mathbf{J}_s}{\rho_s} = -[\phi D_\phi \nabla(\dot{\gamma}\phi) + \phi^2 \dot{\gamma} D_\mu \nabla(\ln \mu)] + f_h \mathbf{u}_{st} \phi$$

$$\dot{\gamma} = \sqrt{\frac{1}{2}(4u_x^2 + 2(u_y + v_x)^2 + 4v_y^2)}$$

Particle Flux

Momentum Balance

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla p - \nabla \cdot (\rho c_s (1 - c_s) \mathbf{u}_{slip} \mathbf{u}_{slip}) + \nabla \cdot [\eta(\nabla \mathbf{u} + \nabla \mathbf{u}^T)] + \rho \mathbf{g}$$

$$\rho = (1 - \phi_s)\rho_f + \phi_s \rho_s$$

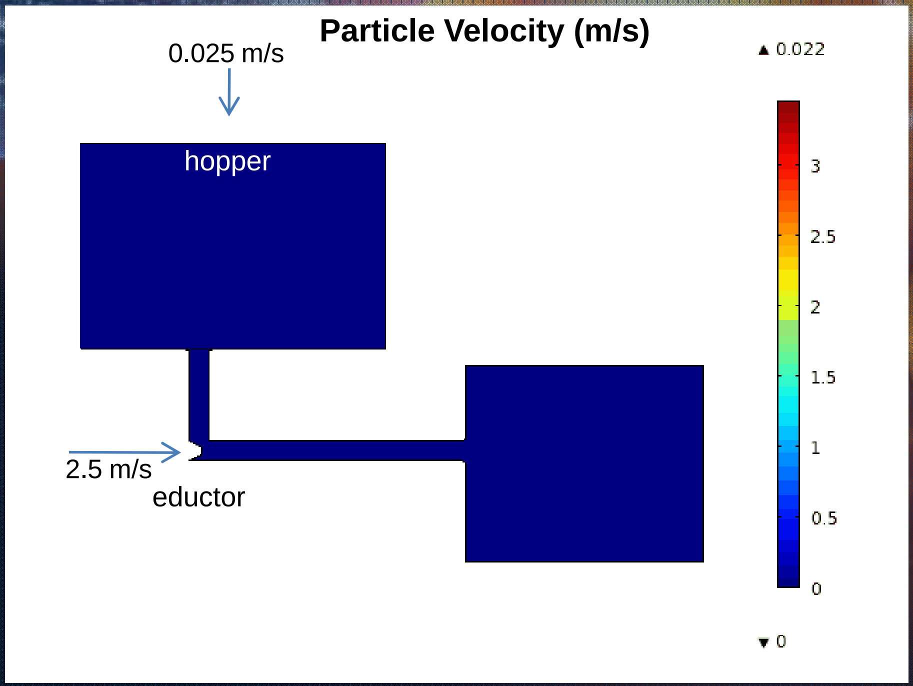
$$\eta = \eta_f \left(1 - \frac{\phi_s}{\phi_{max}}\right)^{-2,5\phi_{max}}$$

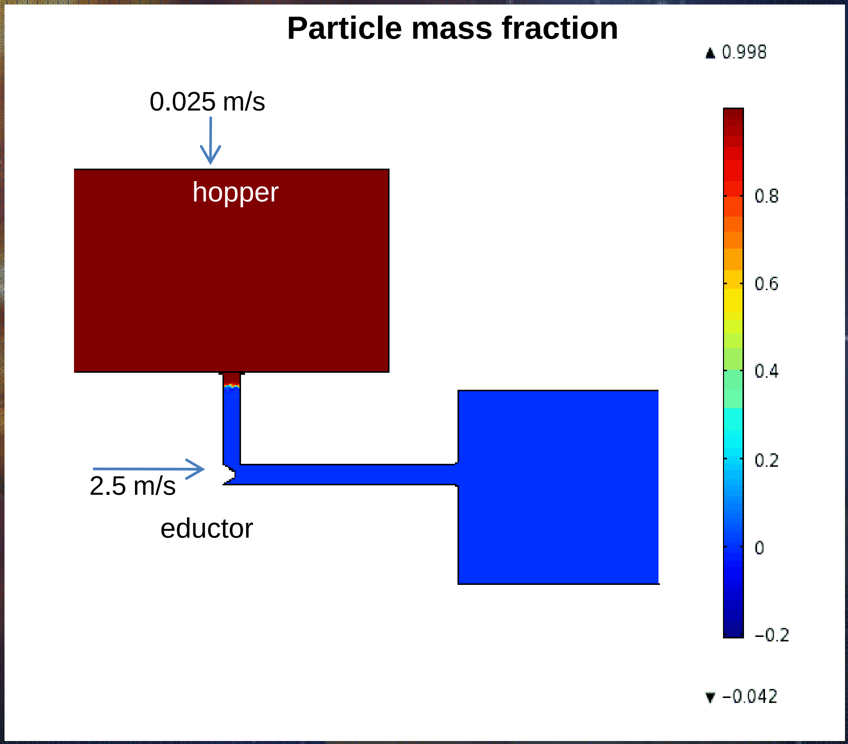
Mixture momentum balance

Key assumptions:

- Incompressible fluid
- Solid phase diluted in the fluid phase
- Momentum balance based on averaged mixture velocity
- Two empirical parameters need to be fitted

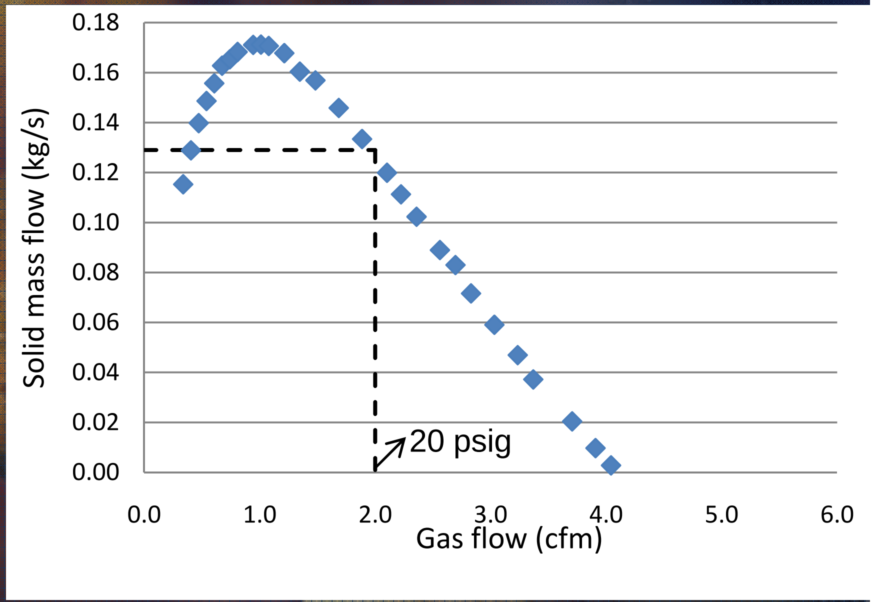
Two-Phase Flow Modeling Result



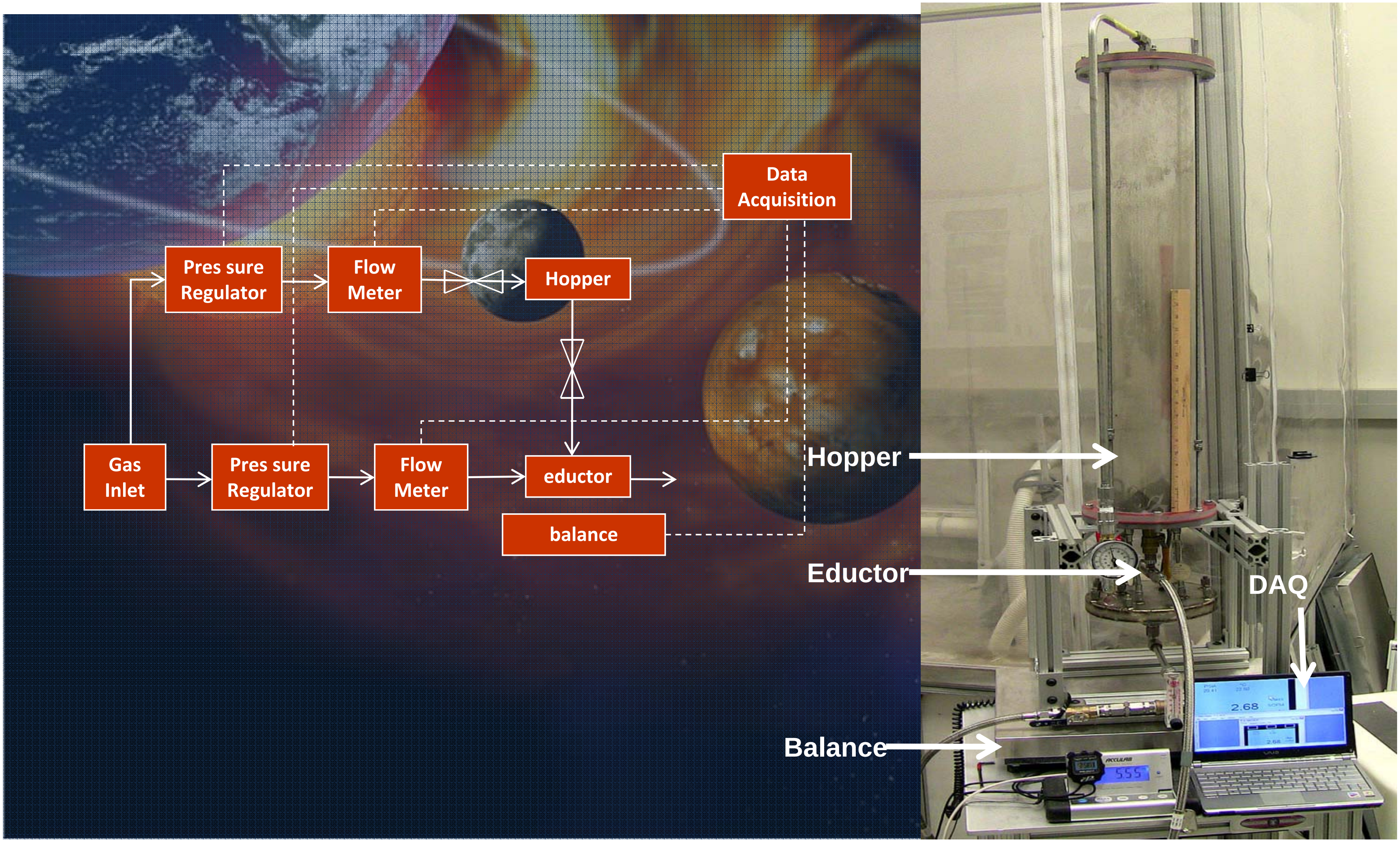


Two-Phase Flow Modeling Results

- Model Predictions:
  - Regolith transport rate is not proportional to eductor gas flow rate
  - Maximum regolith flow rate is reached at relative low flow rates
  - Model predicts maximum solid transport rate at flow rates below manufacturer's recommendation

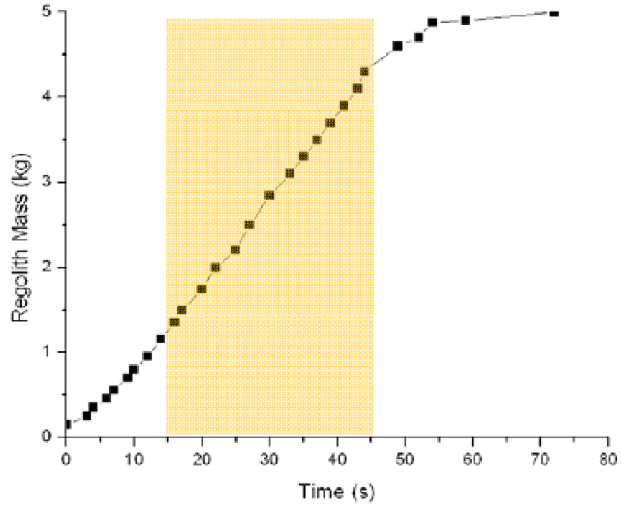


Pneumatic Feed System Experimental Setup

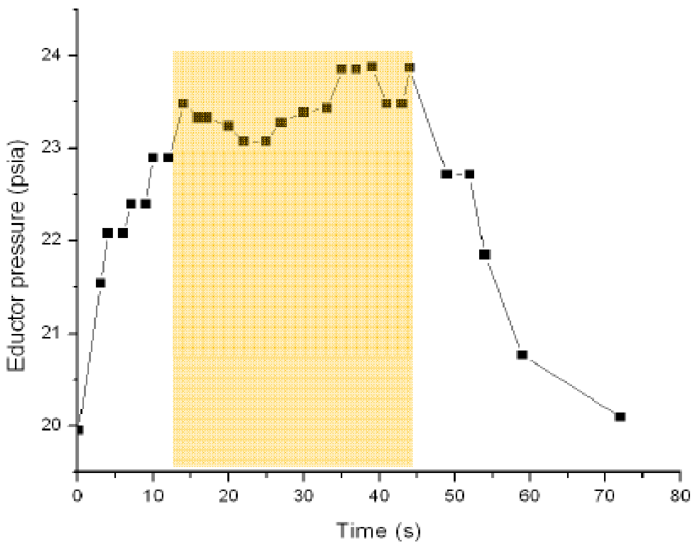


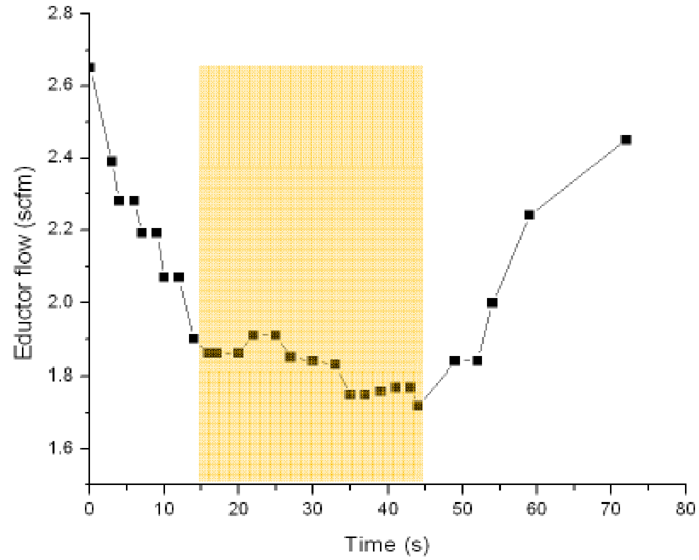
Experimental Results

- As solids are impinged by eductor:
  - eductor pressure increases
  - eductor flow rate decreases
- Steady State reached after 15 sec



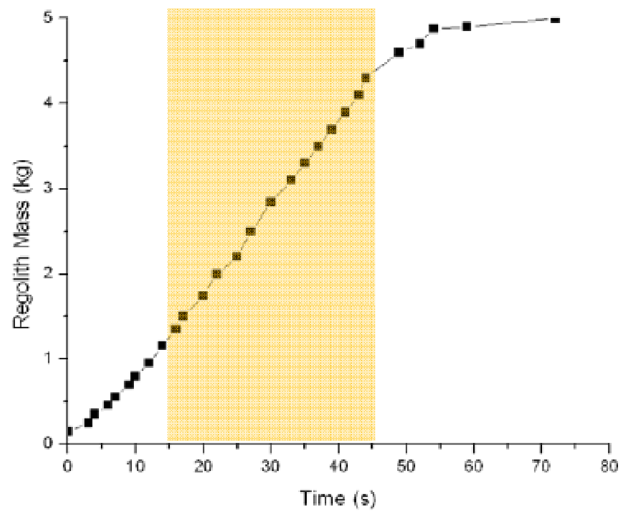
Fluidization/hopper line pressure: 10 psig
Eductor line pressure: 20 psia





Experimental Results

- As solids are impinged by eductor:
  - hopper pressure increases to feed pressure
  - Hopper fluidization flow rate decreases



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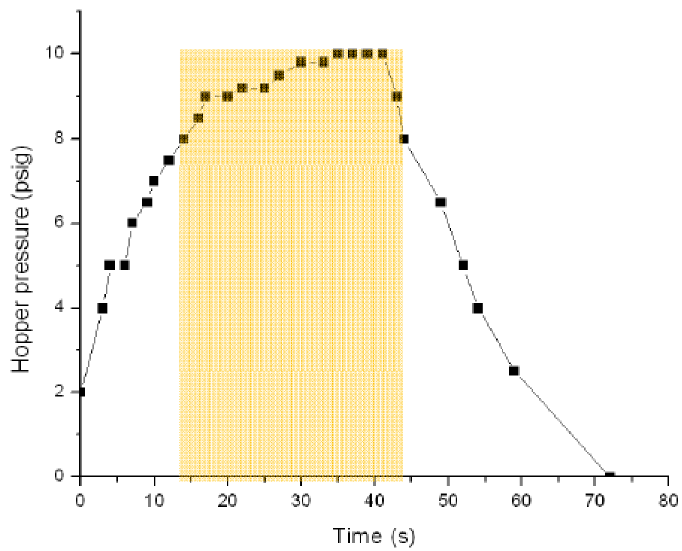
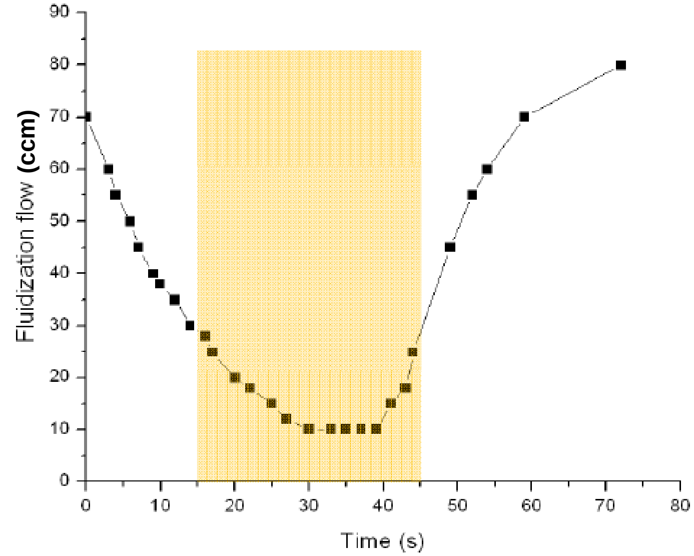
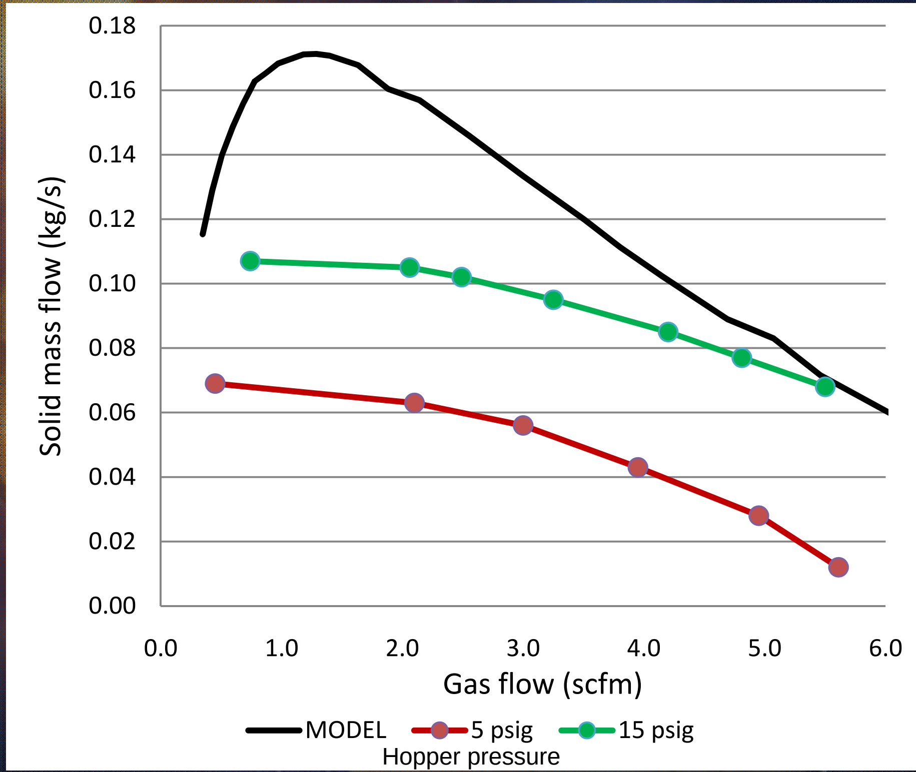




Experimental Results

- Solid transport rate is inversely proportional to eductor gas flow rate
- Solid transport rate is proportional to hopper pressure
- Two-phase flow model agrees with experimental data
  - Boundary conditions for model and experimental test are different
  - One major model assumption, incompressible fluid, is not meet by real system



Solid-Gas Flow Modeling
Kinetic Theory Approach

Mass Balance

$$\frac{\partial}{\partial t}(\rho_i \varepsilon_i) + \nabla.(\rho_i \varepsilon_i \mathbf{U}_i) = 0$$

Phase solid mass balance

$$\sum \varepsilon_i = 1$$

i = gas, solid

Momentum Balance

$$\frac{\partial}{\partial t}(\rho_i \varepsilon_i \mathbf{U}_i) + \nabla.(\rho_i \varepsilon_i \mathbf{U}_i \mathbf{U}_i) = -\varepsilon_i \nabla P + \nabla.\mathbf{T}_i - \beta(\mathbf{U}_i - \mathbf{U}_k) + \rho_i \varepsilon_i \mathbf{g}$$

$$\frac{3}{2}\frac{\partial}{\partial t}(\rho_s \varepsilon_s \Theta_s) + \nabla.(\rho_s \varepsilon_s \mathbf{U}_s \Theta_s) = \mathbf{T}_s : \nabla \mathbf{U}_s + \nabla.(k_s \nabla \Theta) - \gamma_s - 3\beta\Theta_s + \beta\langle \mathbf{C}_g \cdot \mathbf{C}_s \rangle$$

$$\beta = \left(\frac{17.3}{R_e} + 0.336\right)\frac{\rho_g}{d_p}\left|\mathbf{U}_g - \mathbf{U}_s\right|(1-\varepsilon_g)\varepsilon_g^{-2.8}$$

$$R_e = \frac{d_p\left|\mathbf{U}_g - \mathbf{U}_s\right|\rho_g}{\mu_g}$$

Key assumptions:

- Compressible fluid
- Solid phase diluted or concentrated in the fluid phase
- Momentum balance based on individual phases
- Empirical parameters not need to be fitted
- Flexible model

- Work in progress
- Model is in debugging phase

Conclusions

- Current model demonstrate and agrees with experimental data on the relationship of gas flow and solid transport rate.
- Model predicts solid transfer rate is inversely proportional to gas flow rate on the eductor
- At the system level, this findings result in a reduction of gas flow and pressure requirements to compressor
  - Lower power and mass than previously anticipated
- This is a work in progress…