TEXAS STATE UNIVERSITY

Ansys

HuLC
HUMAN LANDER CHALLENGE

Numerical Simulation and Physical Validation of Regolith Ejecta During Plume Surface Interaction

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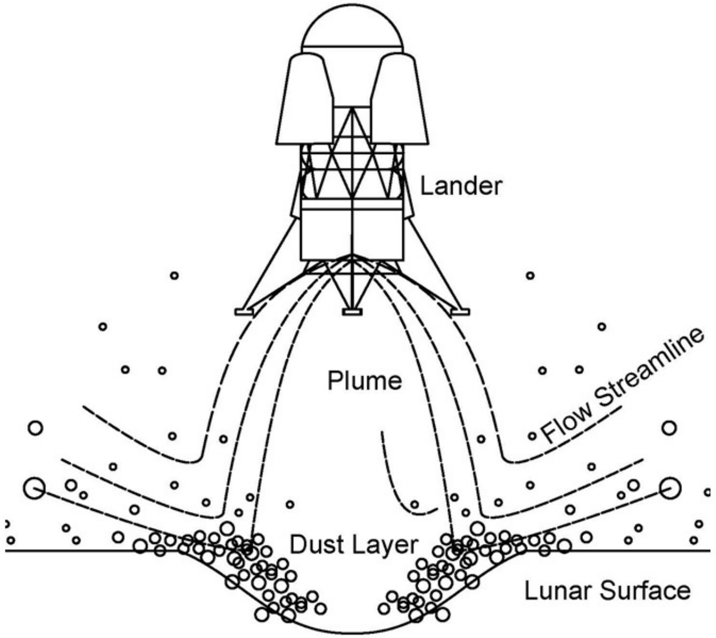
Objective

Adapt the modeling capabilities of Ansys FLUENT to deliver accurate simulations of vacuum plume dynamics, diffusion at the lunar surface, and resulting regolith particle trajectories.

Develop	Develop a CFD-DSMC Hybrid Method User-defined Function for Ansys FLUENT
Simulate	Simulate Lunar Regolith Ejecta
Validate	Validate Numerical Model with Physical Tests



Importance of Direct Simulation Monte Carlo (DSMC)

The Direct Simulation Monte Carlo (DSMC) method employs probabilistic Monte Carlo simulations to solve the Boltzmann equation for fluid flows with finite Knudsen numbers.

DSMC is used:

- High Knudsen number flows ($K_n > 0.01$)
- When continuum assumption of classical fluid dynamics breaks down
- Non-equilibrium effects
- Comprehensive flow data
- Significant parallelizability

Challenges of DSMC:

- Computationally expensive
- Integration with continuum solver
- Validating statistical model
- Typically requires scaling

Non-equilibrium Effects

- Rarefied gas dynamics
- Expansion into vacuum
- Boundary layer separation
- Shock formation

Computational Cost

- Tracking large number of particles
- Large number of collisions
- Memory and Storage Requirements
- Time Step Constraints

Utilizing Ansys FLUENT

There are many software packages and tools that implement DSMC for rarefied gas flows.
DAC, MONACO, DSMC-POEM, SPARTA, NEXUS, DSMCFoam, PDSC++, PHASTA-DSMC, and NSU3D-DSMC…

Why use Ansys FLUENT when it is designed for modeling continuum flow?

- Most widely used computational fluid dynamics software
- Comprehensive multiphysics and multiphase flows
- Efficient solver and load balancing
- Flexibility of user-defined functions (UDFs)
- Optimization for high-performance computing
- Intuitive user interface

Academic Partnership
Ansys® Academic Research Mechanical and CFD

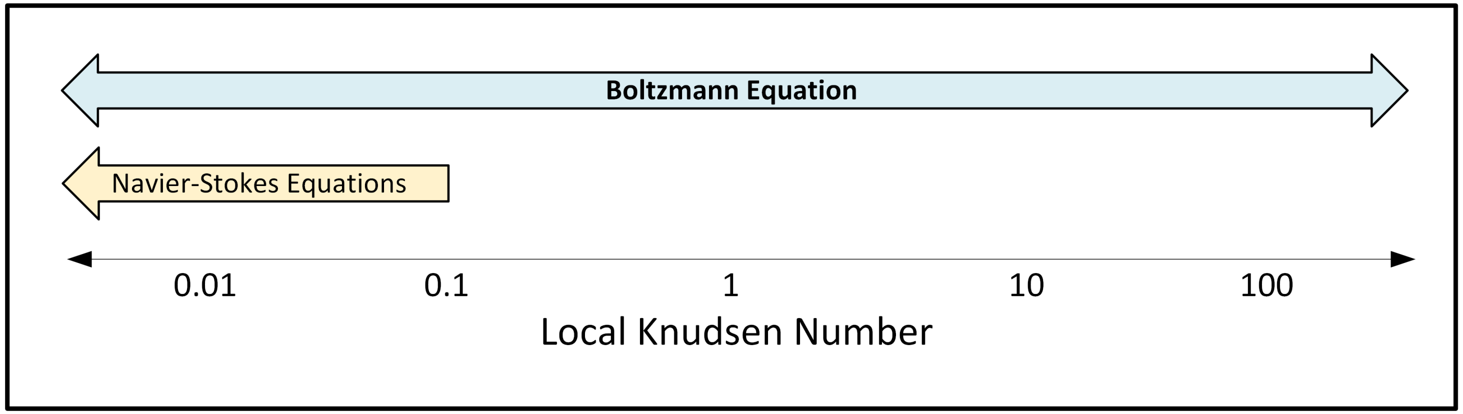
Integrating DSMC in Ansys FLUENT

Implementing DSMC with User-Defined Functions (UDFs)

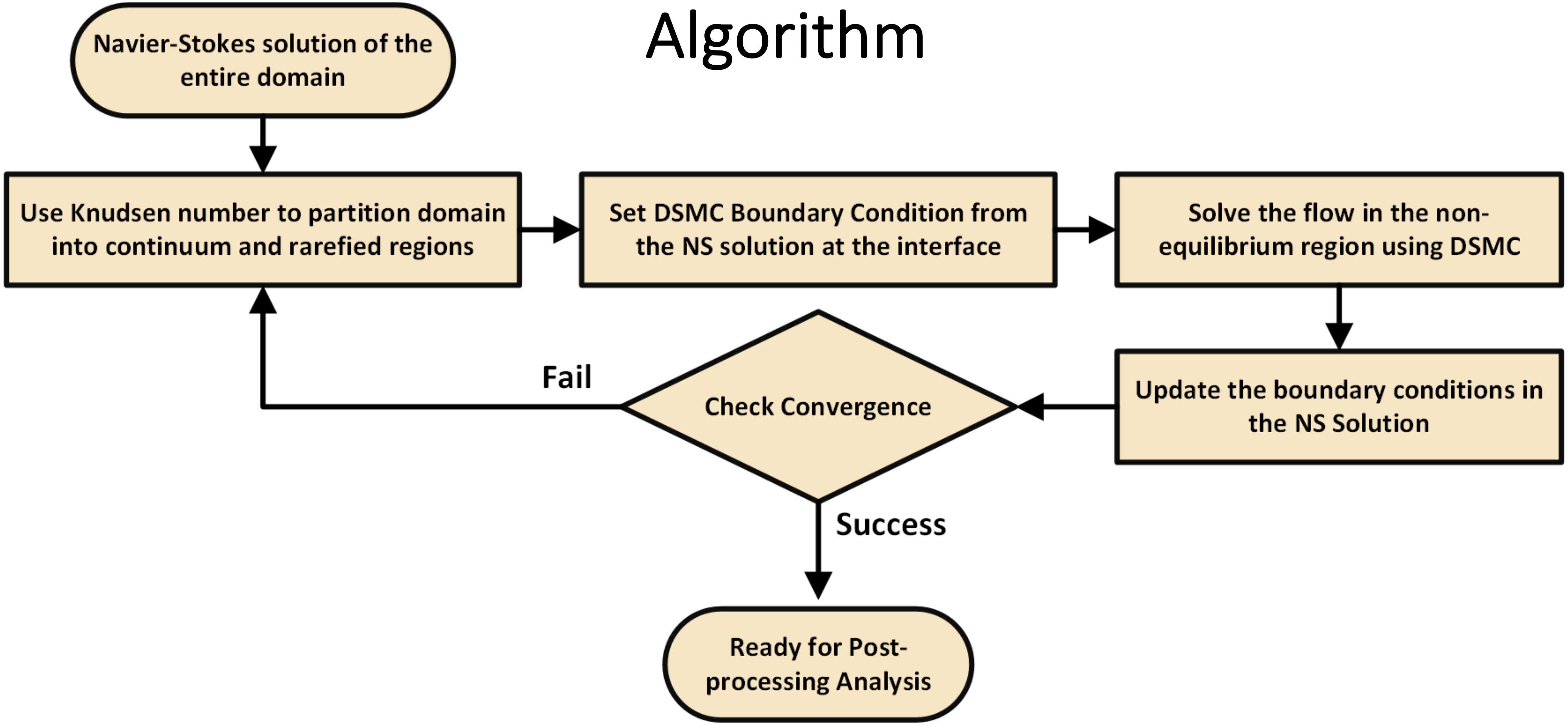
- Leveraging the accuracy and efficiency of the continuum solver for the dense flow regime (Navier-Stokes Equations)
- Utilize a user-defined function to calculate Knudsen numbers
- DSMC function is used to simulate gas molecules and particle interactions with the rarefied region
- Implement DSMC where the Knudsen number exceeds 0.1 (Boltzmann Equation)
- Seamless transition between regimes with hybrid approach

The Knudsen number K_n is determined by the ratio of mean free path λ to a characteristic length scale of the system L_{char}.

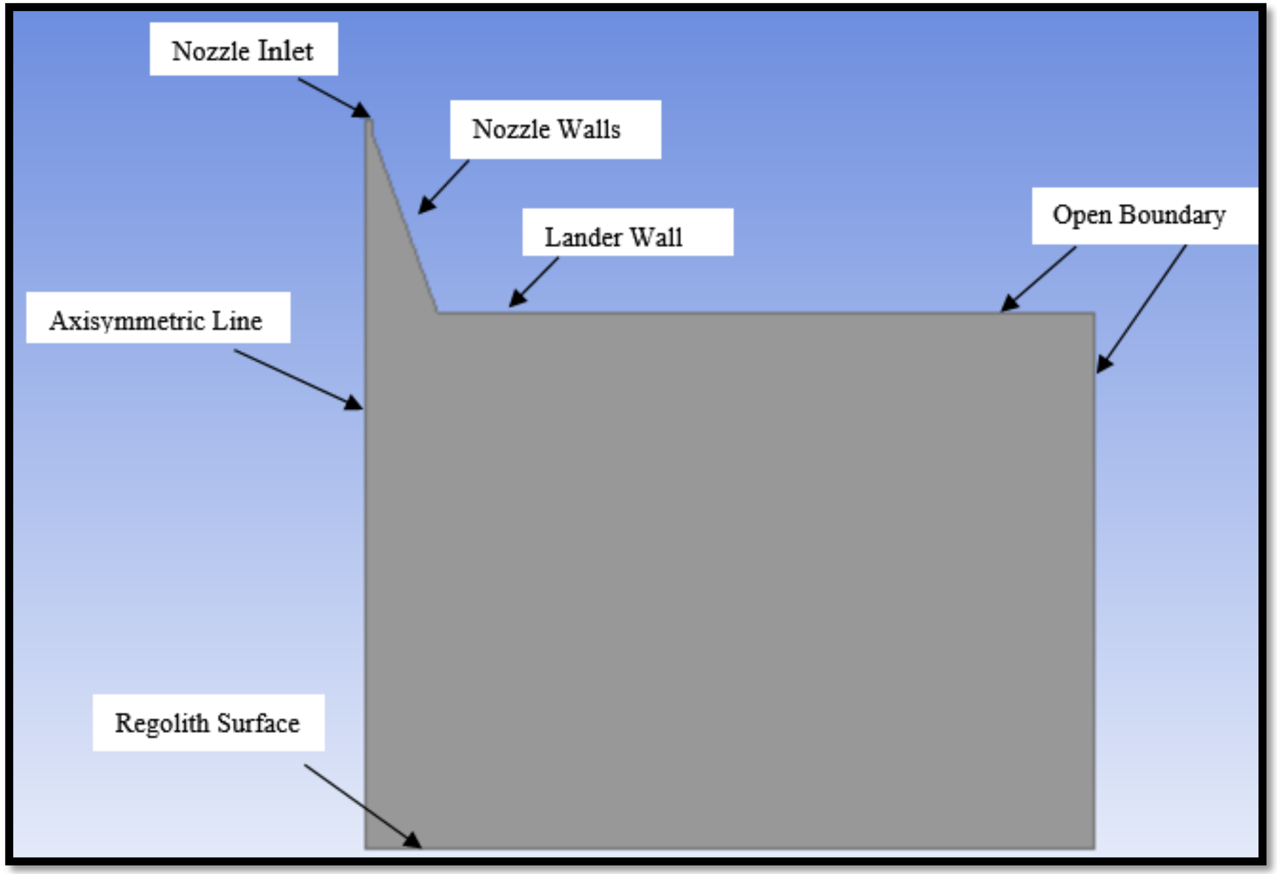
$$K_n = \lambda / L_{char}$$



CFD-DSMC Hybrid Algorithm



Model Design

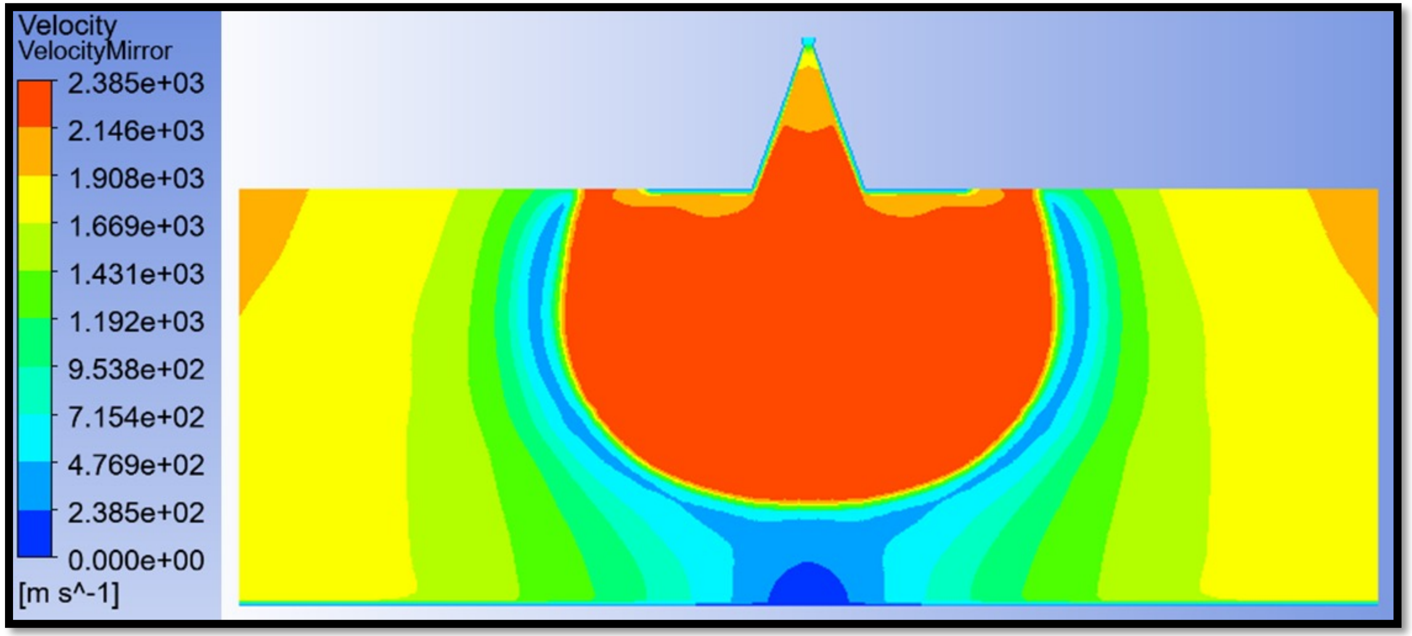


Domain Geometry and Boundary Conditions

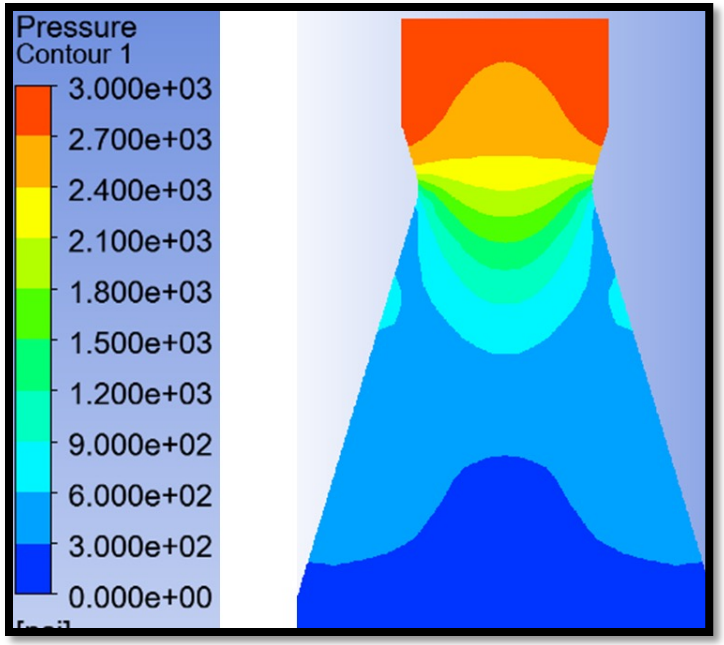
- Nozzle dimensions based on Blue Origin’s BE-7 engine
- Inlet pressure derived from thrust specifications and approximated geometry
- Open boundary in far field
- Axisymmetric along central axis of nozzle
- Domain measures 6 meters by 6 meters
- Several particle layers simulating lunar dust ranging from 10 µm to 70 µm along the bottom region of the domain

Preliminary Results

Plume Velocity and Nozzle Pressure Contours



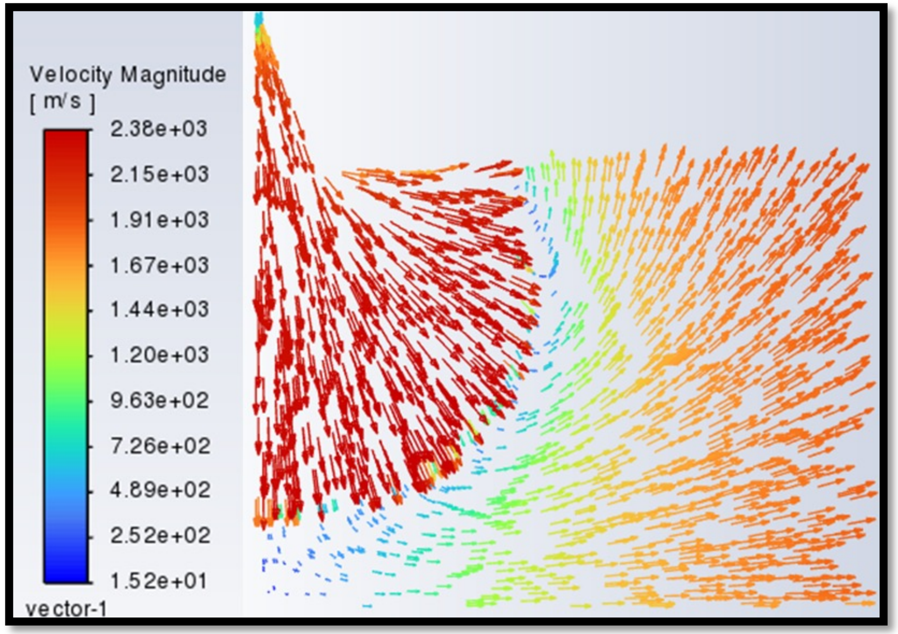
Under high pressure, the plume accelerates through the nozzle’s throat. Upon exiting, it expands and slows before reaching the regolith. After impact, the plume reflects and accelerates diagonally on both sides.

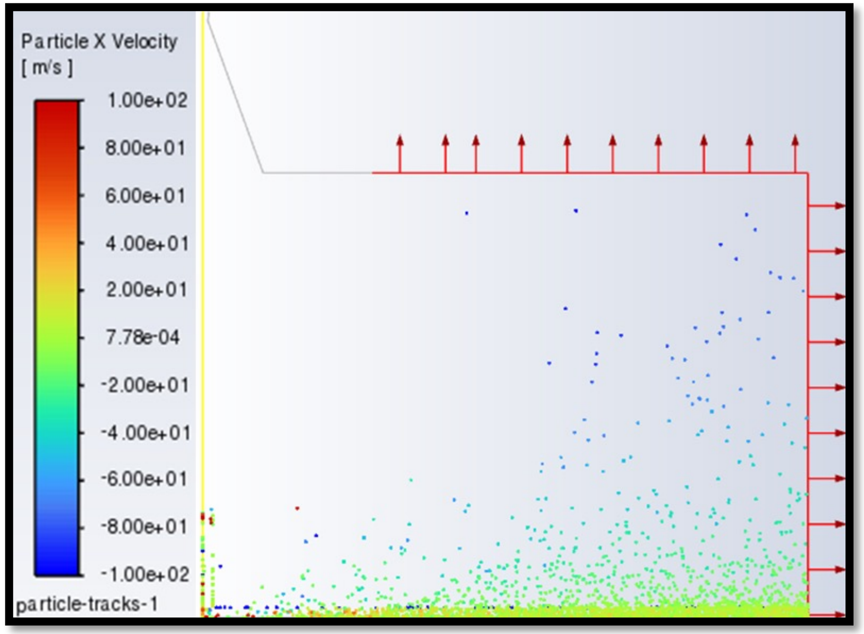


This pressure distribution is typical of fluid flow through a converging-diverging nozzle.

Preliminary Results

Plume Velocity Vectors and Particle Tracking





The plume extends along the nozzle wall, slowing before reaching the regolith. On impact, it rebounds and accelerates diagonally sideways.

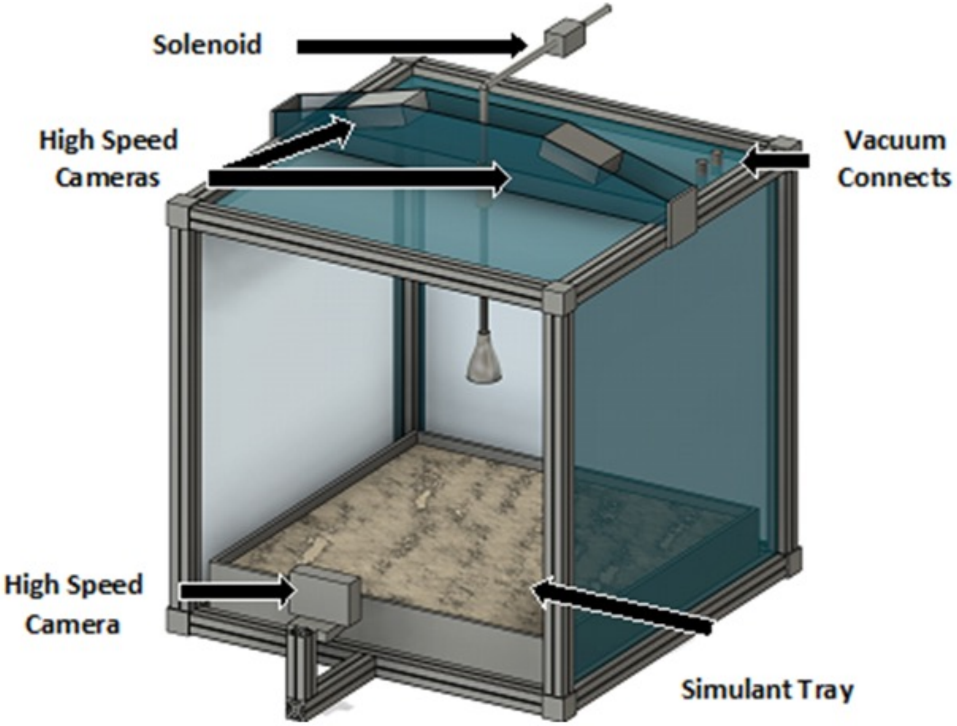
Dust particles on the regolith surface are propelled sideways and upwards by the plume flow, gaining acceleration as they rise.

Validating Simulation Results

Vacuum chamber test setup

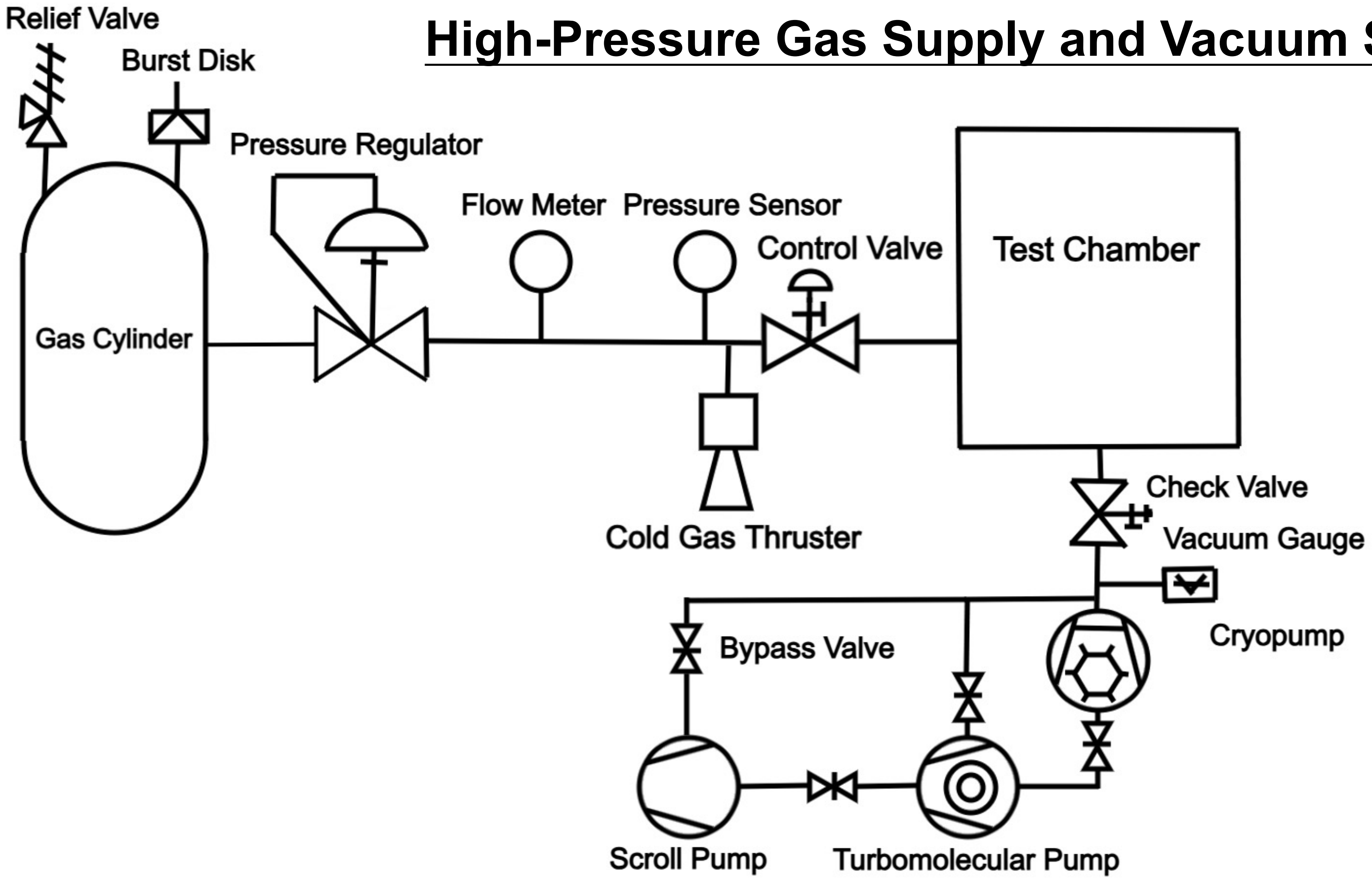
The simulations results are to be validated by a custom test setup involving a spacious vacuum chamber, vacuum pump system, high-pressure gas injection system, particle image velocimetry (PIV) with high-speed cameras, and lunar regolith simulant.

The chamber is constructed from materials capable of withstanding vacuum pressures without deforming or leaking. Aluminum oxynitride glass will be used due to its transparency, high strength and low outgassing properties. Special vacuum-compatible seals and gaskets, often made from materials like Viton or silicone, are used to ensure airtight seals around doors, windows, and other joints. The cube-shaped chamber measures 1 meter by 1 meter by 1 meter.



Experimental setup for numerical validation

High-Pressure Gas Supply and Vacuum System



Achieving Vacuum Environment

Simulating vacuum conditions of the lunar surface:

- Roughing pump: Lowers pressure from atmospheric to rough and medium vacuum (10^-1 Torr to 10^-3 Torr)
- Turbomolecular: Reduces pressure to high or high vacuum (10^-6 to 7.5^-8 Torr)
- Cryopump: Achieves ultra-high vacuum by condensing gases (< 1x10^-8 Torr)
- Pirani vacuum gauge: Accurately measures chamber pressure
- Valves/venting systems: Control air removal and reintroduction, prevent damage from sudden pressure changes

Rough Vacuum
Varian Tri Scroll Pump
Ultimate Pressure 10e-3 Torr

High Vacuum
Pfeiffer HiCube Turbomolecular Pump
Ultimate Pressure 7.5e-8 Torr

Ultra-High Vacuum
ULVAC Cryopump
Ultimate Pressure <1e-8 Torr

Test Setup Regolith

Matching the physical properties of lunar regolith

Lunar surface simulants mimic the physical and chemical properties of lunar regolith. High-fidelity simulants can be expensive and limited in quantity. Balancing realism with availability is important for large-scale testing. Simulants vary in their properties and how accurate they simulate real lunar soil: abrasive wear, testing flow transport, thermal properties, etc.


JSC-1A


LHS-1


NU-LHT-2M

Important factors for simulant selection:

- Particle size distribution
- Particle shape and angularity
- Bulk density and specific gravity
- Mechanical properties
- Availability and cost

Modeling the Rocket Nozzle

Scaling down Blue Origin’s BE-7 Engine

- 3D- printed nozzle replicates BE-7 engine nozzle
- Mounted in testing chamber to mimic Human Landing System engine exhaust
- Cold gas thruster expels inert gases at high velocity
- Simulates exhaust plume safely
- High-pressure gas supply system manages flow
- The exit of the model nozzle has 100 mm diameter and can be printed to different scales as the simulation parameters change through the experiment phase.

BE-7 Rocket Engine

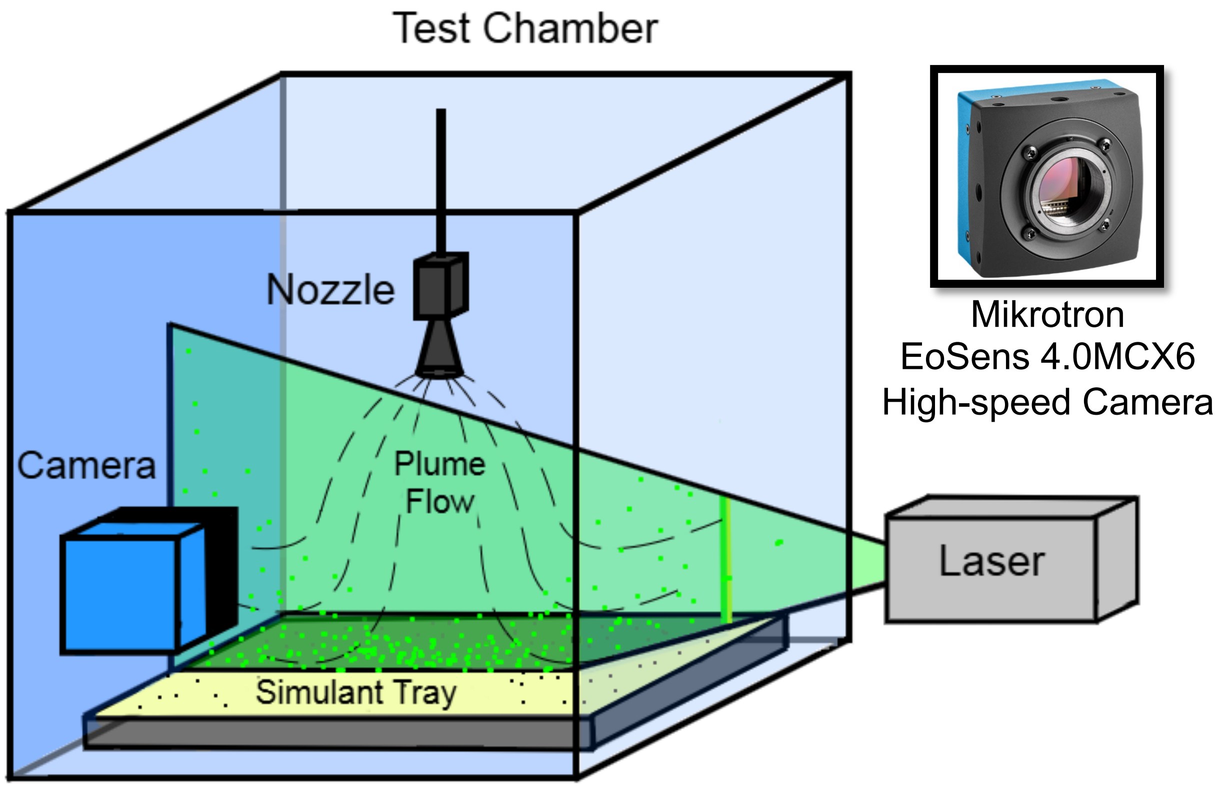
Nozzle Contour Comparison
12:1 scale

100 mm exit diameter

Cold Gas Thruster Nozzle
Section View

Instrumentation and Data Acquisition

Particle Image Velocimetry (PIV) system analyzes particle movement and plume behavior



Mikrotron
EoSens 4.0MCX6
High-speed Camera

Particles illuminated by PIV system

PIV system

- High-speed camera captures up to 38,500 fps
- Plane of laser light illuminates particles in plume flow
- Analyzes particle movement and plume behavior
- Enhances physical validation tests

Data Acquisition System

- Manage and analyze extensive experiment data.
- Understand PSI effects like dust ejection and erosion patterns.
- Standard DAQ systems record pressure data.
- Image acquisition hardware interfaces with high-speed cameras.
- Specialized PIV software extracts velocity information.
- Image analysis software tracks particle trajectories for comprehensive analysis.

Testing Procedure

1. Evacuate the test chamber to achieve a pressure in the range of approximately 10e-6 to 10e-9 Torr.
2. Expel plume gas onto regolith surface using cold gas thruster (0.1 second impulse duration).
3. Plume gas stabilizes into steady state operation within approximately 60 milliseconds.
4. Meticulously monitor and record plume behavior (velocity, pressure, particle velocities, trajectories).
5. Tests designed to be adaptable, allowing for nozzle height adjustments to explore different configurations.

Milestones and Timeline

1. **Months 1-3**: Develop the project plan, set up the numerical simulations
2. **Months 4-9**: Finalize the experimental configuration and procure necessary equipment, execute experiments for model validation and run numerical simulations with refined parameters based on initial validation results
3. **Months 10-12**: Analyze experimental data and refine the numerical model by incorporating any improvements identified during validation, and compile findings into a comprehensive report and presentation
4. **Cost Estimation**: Total annual operating costs are about $195,000. The operating costs include personnel costs, software licenses, computing resources, equipment and materials and lab space rental

Conclusion

1. The psi phenomenon associated with the lunar lander's landing process is simulated using Ansys FLUENT.
2. The Discrete Phase Model (DPM) is utilized to track particle trajectories, while the Direct Simulation Monte Carlo (DSMC) model is employed to capture the plume flow within the rarefied area.
3. Testing devices, instruments, and procedures for future physical validation tests are developed.
4. Preliminary numerical results of plume fluid flow and dust particle trajectories indicate that the current FLUENT model accurately reflects nozzle flow and plume surface interactions.