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

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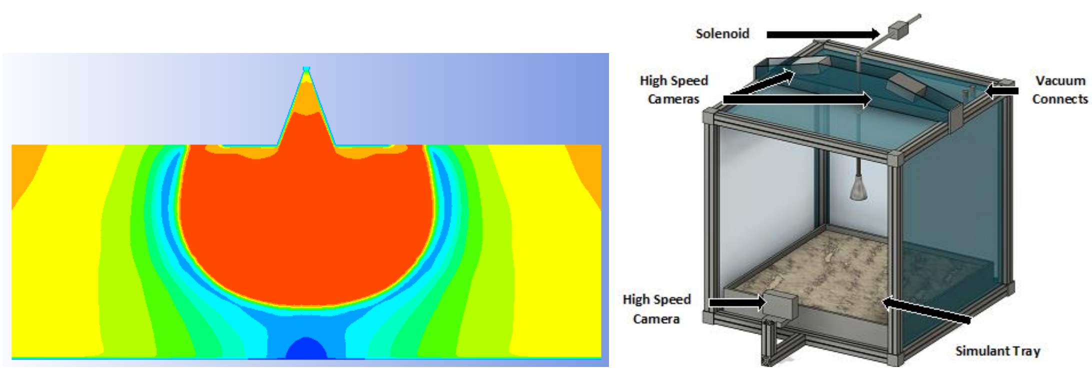


Numerical Simulation and Physical Validation of Regolith Ejecta During PSI

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

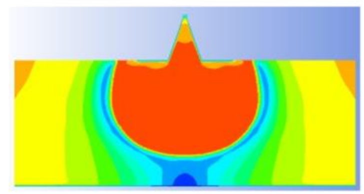
Major Objectives & Technical Approach

- Objectives: to develop a comprehensive model encompassing the plume dynamics in the nozzle, vacuum plume diffusion erosion on the lunar surface and near field dust spray.
- Technical Approach

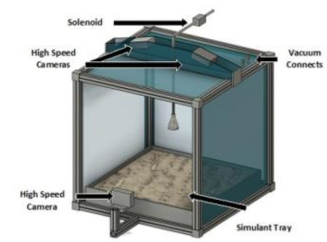
1. Utilization of FLUENT: The commercial CFD package FLUENT serves as the foundation for establishing a robust numerical model to simulate plume -surface interaction.
2. Experimental Validation: Parallel to numerical simulations, experiments are meticulously conducted to validate the fidelity of the numerical model.

Image/Graphic:

- Image/Graphic depicting the concept.



Numerical Simulation of PSI



Experimental Configuration for Modeling Validation

Key Design Details & Innovations of the Concept

- Design Details

1. Create an axisymmetric geometry representing the exhaust nozzle and its surrounding and apply high -quality meshing to capture the complex flow phenomena and surface interactions adequately.
2. Develop a user-defined function of the DSMC method integrated to FLUENT to simulate the rarefied plume flow and utilize the discrete phase model (DPM) to simulate the trajectory of regolith particles.
3. Design an experimental setup to validate the numerical simulations, ensuring alignment between simulated and real -world scenarios.

- Innovations

The mix of axisymmetric shapes, precise meshing, and advanced numerical methods integrated into FLUENT creates a solid modeling of plume -surface interaction.

Summary of Schedule & Costs for the proposed solution's path to adoption

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.

Costs: 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.

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1. Introduction

1.1 Problem Statement

The present study aims to develop a comprehensive understanding of the dynamics involved in plume-surface interactions on the lunar surface. Utilizing the Ansys CFD package FLUENT, we will create a detailed numerical model that simulates the behavior of the plume as it exits the nozzle, diffuses in a vacuum, and interacts with the lunar regolith. The objectives of this study include:

1. **Developing a CFD-DSMC Hybrid Method**:
   - Integrate the Direct Simulation Monte Carlo (DSMC) method for gas flow in the rarefied region and the Navier-Stokes equations for gas flow in the continuum region. This hybrid approach will accurately simulate the dynamics of the gas flow as the plume is injected from the nozzle, enabling precise tracking of the plume spray trajectory in a lunar-like vacuum environment.

2. **Simulating Lunar Regolith Ejecta**:
   - Utilize a discrete phase model (DPM) in FLUENT to simulate the ascent and dispersion of regolith particles caused by plume impingement. This simulation will help understand the erosion, displacement, and potential damage to lunar infrastructure due to the exhaust plume.

3. **Experimental Validation**:
   - Develop experimental devices, measurement setups, and testing approach to confirm the accuracy of the numerical models for plume-surface interaction in a lunar-like vacuum. Experimental validation will ensure the simulations accurately represent real-world conditions encountered during lunar exploration, thereby building confidence in the computational models and their predictions.

1.2 Background

The lunar lander expels high-velocity gas from its engine in the form of a plume. The behavior of this plume is influenced by the nozzle design and the ambient conditions, such as the vacuum of space or the thin atmosphere of another planet. As the plume exits the nozzle, it expands and interacts with the surrounding environment. In a vacuum, the plume expands rapidly due to the lack of atmospheric pressure. As shown in Figure 1, upon impacting the surface, the high-velocity gas can dislodge surface particles, a process known as regolith ejection on the Moon or dust and soil erosion on other planetary bodies. This interaction leads to the creation of a cloud of particles, which can be propelled at high velocities. The extent of erosion and the characteristics of the ejected particles depend on factors such as the exhaust velocity, the angle of impingement, and the properties of the surface material [1-2]. The impingement of the rocket plume can create craters or depressions on the surface. The size and shape of these craters are determined by the energy and duration of the plume impact. Repeated or sustained impingement can lead to significant surface modifications, affecting the stability and integrity of the landing site. The ejected particles can pose hazards to nearby equipment and infrastructure. High-velocity dust and debris can damage sensitive instruments, abraded surfaces, and contaminate other mission-critical components [3-4]. Therefore, PSI is a multifaceted phenomenon involving the interaction of high-energy rocket exhaust with a planetary surface, leading to significant erosion, particle ejection, surface modification, and potential hazards [5-7]. Studying and understanding PSI is crucial for the design and success of planetary landing missions, as it impacts both the immediate landing zone and the long-term sustainability of surface operations.

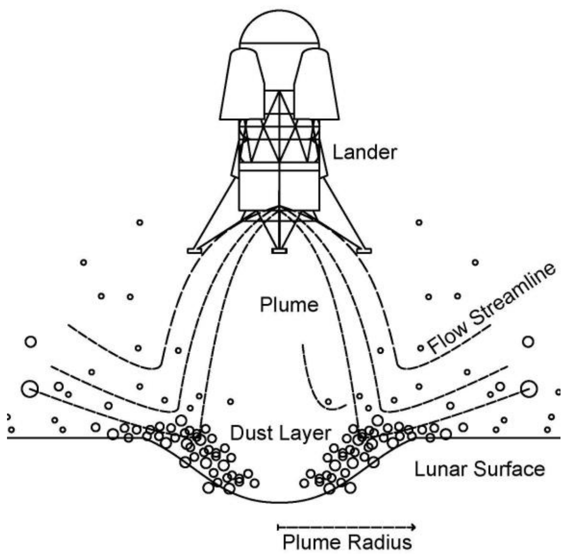


Figure 1 Diagram showing a plume impact and the resulting flow of dusty gas caused by solid particle ejection from the lunar regolith during the lunar landing

The exhaust plume of a lunar lander encompasses different flow regimes, from the high-density, continuum flow near the nozzle (where CFD is effective) to the rarefied gas conditions in the vacuum of space (where DSMC is more appropriate). CFD is well-suited for solving the Navier-Stokes equations in the dense flow regime, while DSMC is ideal for simulating molecular interactions in the low-density regime. The hybrid approach allows seamless transition between these regimes [8-10]. Carlson et al. [8] developed a hybrid CFD-DSMC method for modeling continuum-rarefied flows. The algorithm computes a breakdown parameter locally to assess the validity of the continuum assumption and activates the DSMC component when this parameter exceeds a certain threshold. The DSMC algorithm employs Information Preservation (IP) and ghost cells to exchange macroscopic flow properties accurately and efficiently with the CFD algorithm. Tani and Ohmaru [9] conducted hybrid Navier–Stokes (N-S) and DSMC simulations to predict surface pressures and heat fluxes caused by plumes impinging on spacecraft at actual length scales. Their study effectively demonstrated the utility of the hybrid N-S/DSMC technique for assessing risks and exploring new concepts related to plume impingement on spacecraft, including interactions between plumes and between plumes and surfaces. Rahimi et al. [10] conducted a study focusing on the interaction between the near-field rocket plume and the lunar surface, examining the resulting regolith erosion and particle dispersal. They employed the finite volume method to analyze how the rocket nozzle's plume impinged on the lunar surface. To model the influx mass flow rate of dust particles caused by excess shear stress, they introduced the Roberts erosion model. Additionally, they utilized a Lagrangian framework to handle the particulate phase, employing the discrete phase model for this purpose.

The current investigation introduces a hybrid Computational Fluid Dynamics (CFD) and Direct Simulation Monte Carlo (DSMC) model integrated into FLUENT. This model aims to tackle the challenges posed by Plume-Surface Interactions (PSI) encountered in NASA's lunar exploration missions. It offers valuable insights into plume dynamics, surface erosion, and dust spray behavior. Furthermore, the study validates these insights through experiments. Ultimately, these contributions aid in the development of more robust and reliable mission planning strategies as well as spacecraft design methodologies.

2 Modeling of Regolith Ejecta During Plume Surface Interaction

2.1 Physical Model

The BE-7 engine [11], developed by Blue Origin for the Blue Moon lunar lander, features a nozzle designed for efficient propulsion in space, as shown in Figure 3. The nozzle is hydraulically formed into a bell shape with a specific cone angle of 40 degrees. The throat diameter of the BE-7 engine is 0.1 meters (10 centimeters), and the outlet diameter is approximately 1.2 meters. These specifications enable the engine to generate 10,000 pounds-force (lbf) of thrust.

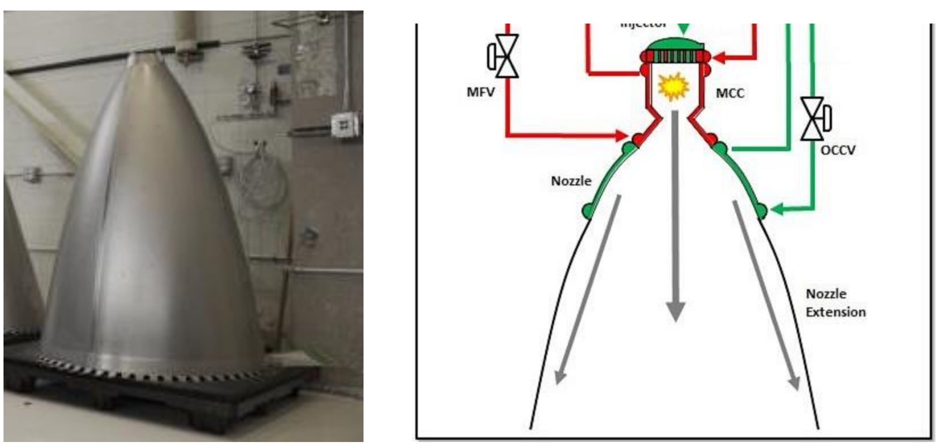


Figure 3 Computational Domain of the PSI Modeling [11]

The computational domain for the BE-7 nozzle and its surroundings, illustrated in Figure 4, is axisymmetric, encompassing both the geometry of the exhaust nozzle and its surrounding environment. Due to the nozzle's symmetry, only half of the entire domain is generated for the simulation. The nozzle is divided into two distinct regions: a convergent section, where the flow accelerates from an initial subsonic velocity to the sonic condition at the throat, and a divergent section, where the flow expands to the outlet in a supersonic regime. In this configuration, both the convergent and divergent angles are 20 degrees.

The plume gas is introduced at the inlet with a fixed pressure of P0 = 3000 psi and a temperature of T0 = 3200 K, while a vacuum condition is assumed outside the nozzle. The walls are modeled as isothermal at T1 = 300 K.

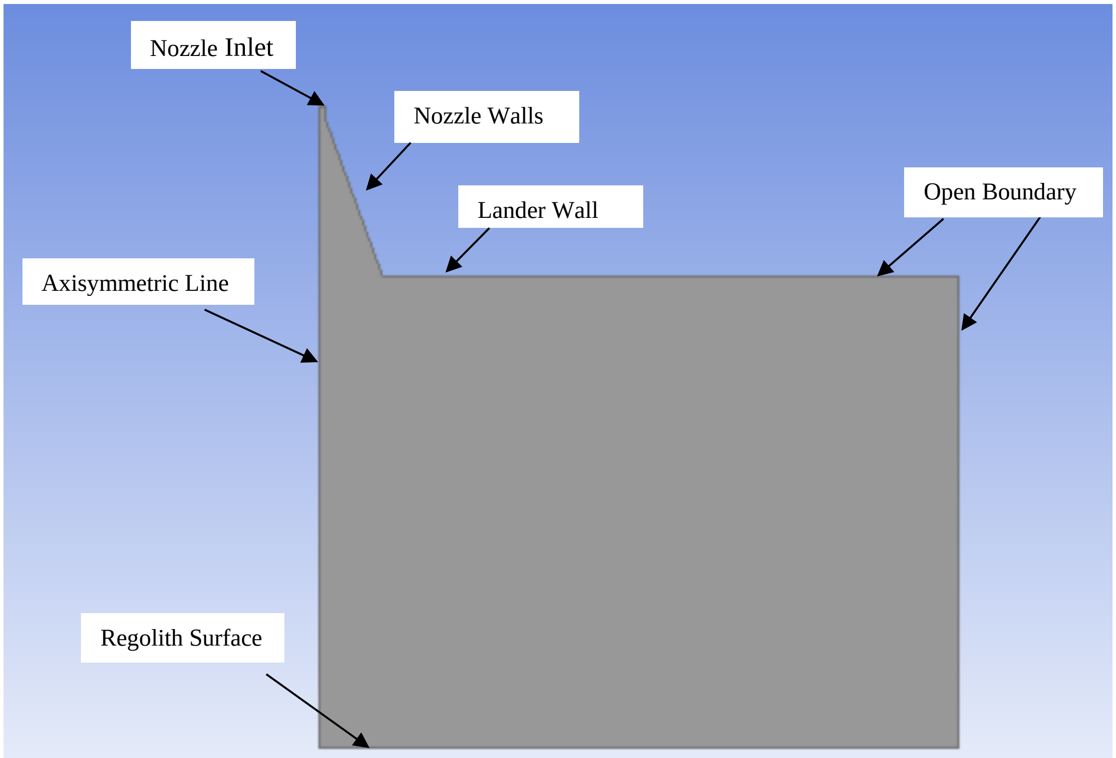


Figure 4 Computational Domain of the PSI Modeling

2.2 Hybrid CFD-DSMC algorithm

To accurately simulate the plume flow after it exits the nozzle, a hybrid CFD-DSMC algorithm is developed in this study. In this approach, the region near the nozzle, which is characterized by a quasi-equilibrium continuum gas flow, is computed using the Navier-Stokes (NS) equations in FLUENT. In contrast, the region farther from the nozzle, where the flow becomes a non-equilibrium rarefied gas, is handled using the DSMC method. The interface between the continuum flow and the rarefied flow is determined by the breakdown parameter, the Knudsen number.

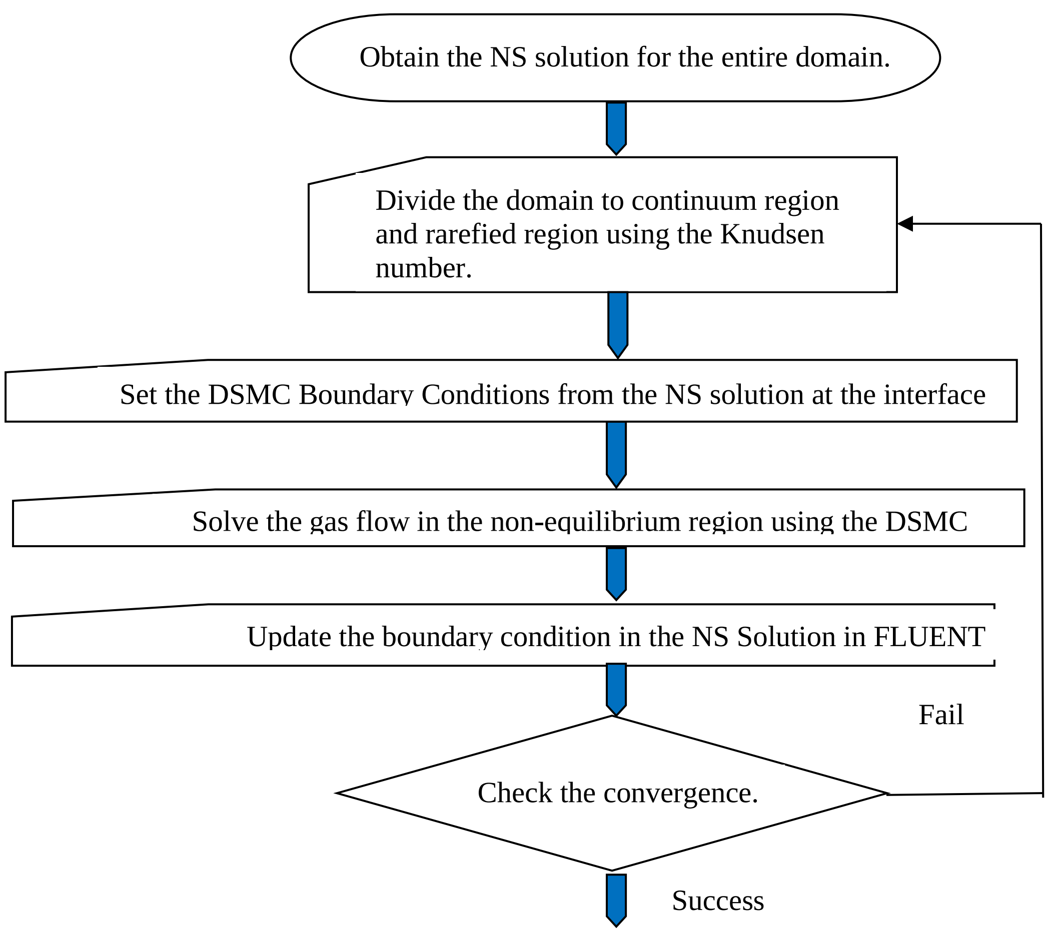
The Knudsen number is a crucial dimensionless parameter used to characterize the boundary conditions of the nozzle jet flow in this study. It is defined as the ratio of the mean free path λ to a characteristic length scale L_{char} of the fluid mechanical system:

$$Kn = \lambda / L_{char} \quad (1)$$

This number provides a numerical assessment of whether the continuum hypothesis can be applied. The mean free path is the average distance a molecule travels before colliding with another molecule. If the characteristic length of the fluid system is comparable to the mean free path (i.e., $Kn \approx 0.1$), the fluid cannot be treated as a continuum.

The Knudsen number is particularly important for evaluating the boundary conditions of fluid flows. In many cases, the flow at the nozzle wall adheres to the no-slip boundary condition, meaning there is no relative motion between the wall and the adjacent fluid layer. This condition holds when the characteristic length of the fluid system is much larger than the mean free path, typically when $Kn < 0.001$. However, as the characteristic dimension of the fluid system approaches the mean free path ($0.001 < Kn < 0.1$), there is some relative movement between the wall and the fluid layer directly in contact with it, resulting in a slip boundary condition. For Knudsen numbers greater than 0.1, the continuum assumption breaks down entirely, and the gas flow must be described using statistical methods rather than continuum mechanics.

The flowchart of the hybrid CFD-DSMC algorithm is shown in Figure 5.



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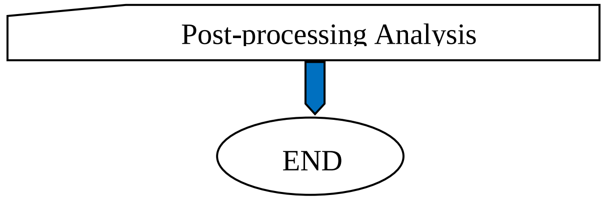
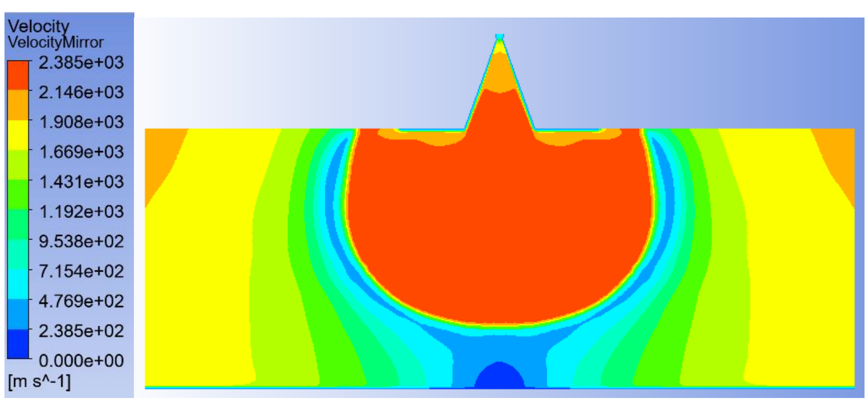


Figure 5 Flowchart diagram of numerical modeling using ANSYS Fluent

2.3 Preliminary Result Analysis

In the simulation, the nozzle's elevation from the top to the regolith surface measures 6 meters, and the computational domain spans a width of 6 meters. Four layers of dust blanket the regolith surface. The dust particles vary in size from 10 micrometers to 70 micrometers, with an average size of 50 micrometers. Open boundary pressures are maintained at zero, while the nozzle inlet pressure is set to 3000 psi. the nozzle walls are no slip walls.

Figure 6 illustrates the plume velocity distribution across the entire domain, along with the pressure distribution in the vicinity of the nozzle. As shown in Figure 6(a), under high pressure, the plume accelerates through the nozzle's throat. Upon exiting the nozzle, the plume expands, and its velocity decreases before reaching the regolith surface. After impacting the regolith, the plume reflects and accelerates diagonally on both sides. As illustrated in Figure 6(b), in the converging section (above the throat), the plume is compressed, leading to an increase in velocity and a decrease in pressure. In the diverging section (below the throat), the plume expands, which further increases its velocity and decreases its pressure. This pressure distribution is typical of fluid flow through a converging-diverging nozzle.



(a)

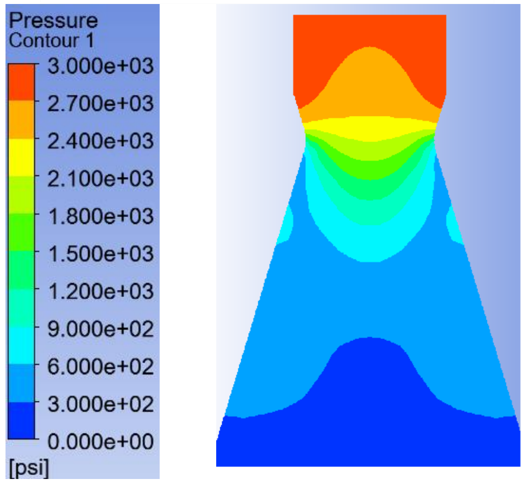
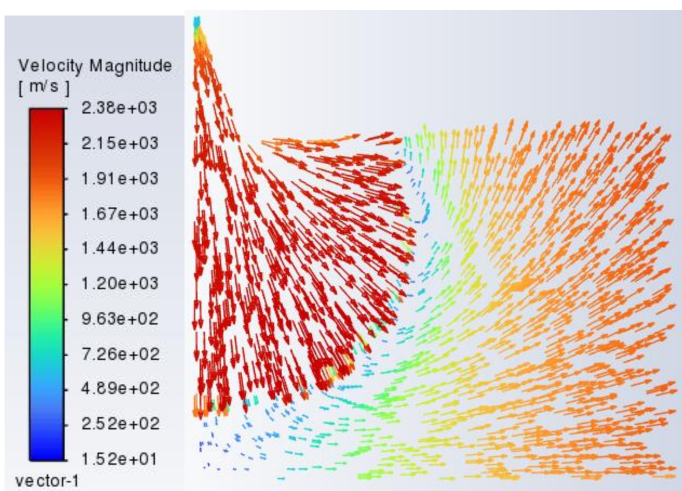
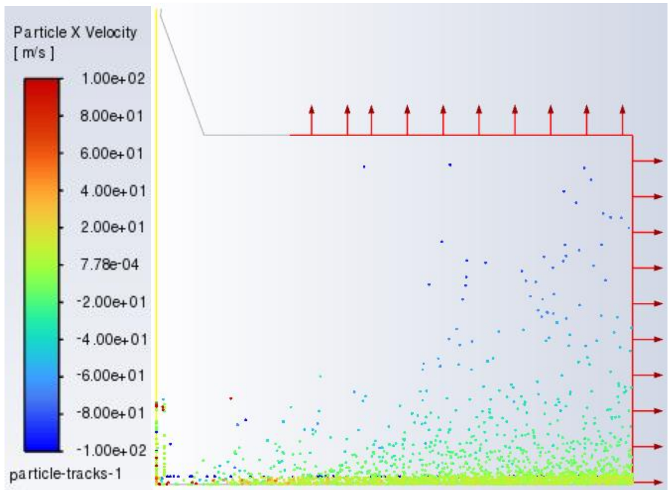


Figure 6: (a) Plume velocity distribution across the entire domain and (b) pressure distribution in the area near the nozzle

Figure 7 illustrates the plume flow vectors and dust particle trajectories across the entire domain. As shown in Figure 7(a), the plume flow extends along the direction of the divergent nozzle wall, gradually slowing down before reaching the regolith surface. Upon collision with the regolith, the plume bounces off, triggering a diagonal acceleration of the flow sideways. In Figure 7(b), the dust particles on the regolith surface are propelled sideways and upwards by the plume flow, gaining acceleration as they rise.



(a)



(b)

Figure 7: (a) Plume flow vectors, and (b) dust particle trajectories throughout the entire domain

3 Physical Validation

3.1 Experimental Setup

An experimental setup for testing PSI on lunar regolith to validate and calibrate the above numerical model in a near-vacuum environment is illustrated in Figure 8.

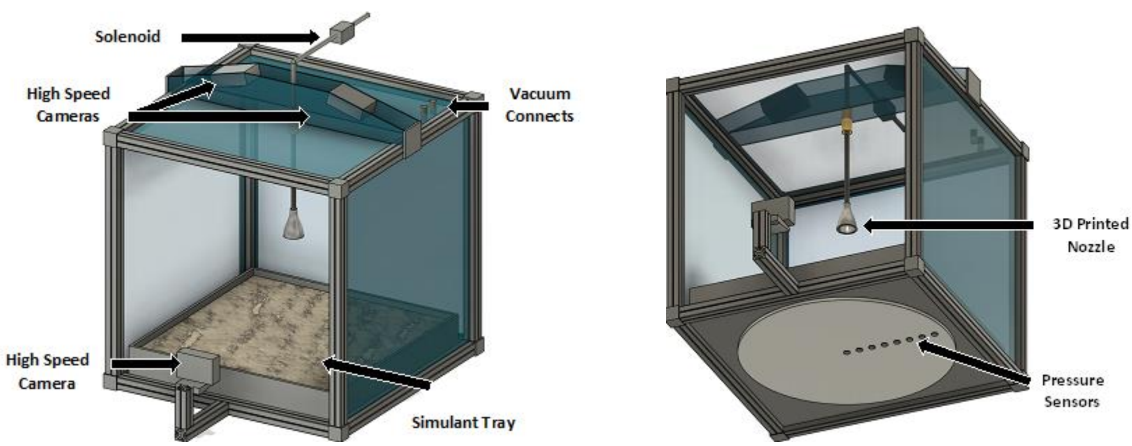


Figure 8: Testing chamber measuring the plume surface interactions

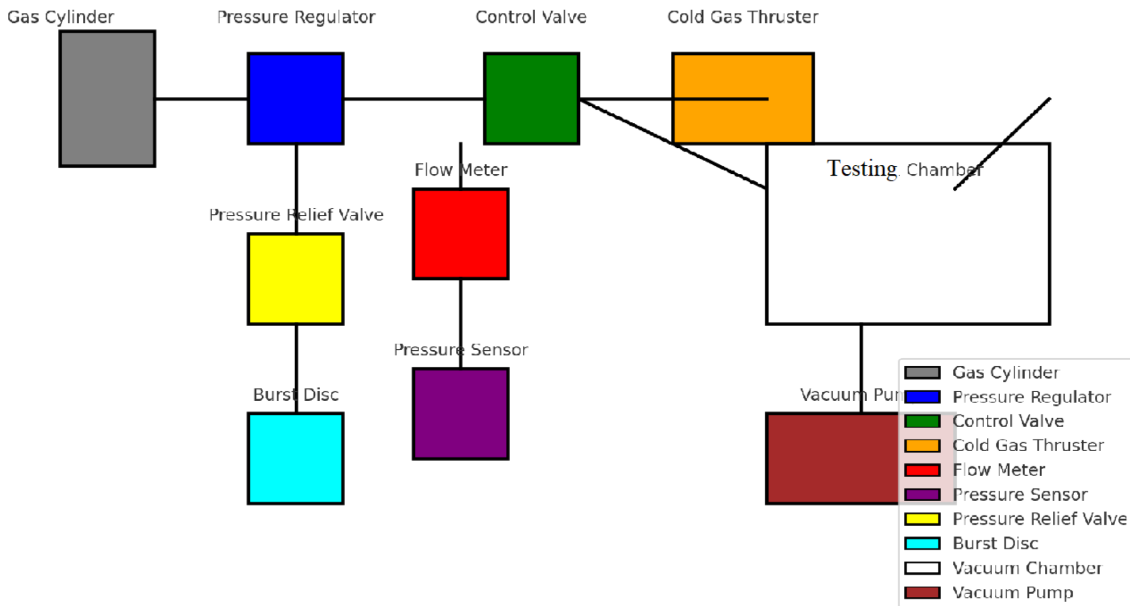


Figure 9: High-Pressure Gas Supply and Vacuum System for PSI Testing

The test chamber for studying the Plume Surface Interaction (PSI) phenomenon during lunar lander touchdowns is designed to replicate lunar landing conditions and study the interactions between the rocket exhaust plume and the lunar surface. The size of the test chamber is 6 meters by 6 meters by 6 meters.

The chamber is constructed from materials capable of withstanding vacuum pressures without deforming or leaking. Aluminum oxynitride glass will be due to its transparency, 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. Here are the key components and aspects of such a chamber.

1. **Vacuum Environment:** The chamber must simulate the near-vacuum conditions of the lunar surface. This is crucial to accurately replicate how the rocket exhaust behaves in the absence of atmospheric pressure.

   Initially, a roughing pump (usually rotary vane or scroll pump) is used to lower the pressure from atmospheric levels to the rough vacuum range (around 10^-3 to 10^-1 Torr). The pump is efficient for handling large volumes of air but can't achieve the ultra-low pressures needed.

   After the roughing stage, a turbomolecular pump or diffusion pump is employed to further reduce the pressure to high or ultra-high vacuum levels (down to 10^-6 to 10^-9 Torr). The pump works by using high-speed rotating blades to impart momentum to gas molecules, pushing them out of the chamber.

A cryopump which uses extremely cold surfaces to condense gases is used to achieve the ultra-high vacuum. The pump is effective at capturing residual gas molecules that other pumps might miss.

A Pirani vacuum gauge is used to measure the pressure inside the chamber accurately. It helps in monitoring the evacuation process and ensuring the desired vacuum level is achieved.

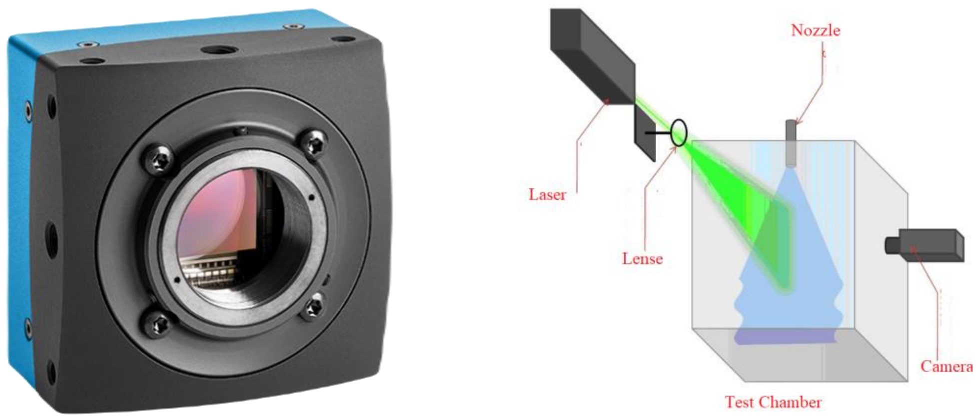
Valves and venting systems are integrated to control the rate at which plume air is removed or reintroduced into the chamber, preventing damage to the chamber or test equipment from sudden pressure changes.

By following these steps, a near-vacuum environment that accurately simulates lunar conditions can be created in the PSI testing chamber, enabling precise study of the interactions between the rocket exhaust plume and lunar regolith.

2. **Lunar Regolith Simulant:** The surface inside the chamber is covered with a material that closely mimics the particle size, shape, distribution, and physical and chemical properties of actual lunar soil (regolith). Based on these similarities, we will use JSC-1A (developed by NASA Johnson Space Center), LHS-1 (developed by the Exolith Lab at the University of Central Florida), or NU-LHT-2M (developed by NASA and the University of Colorado Boulder) as the lunar regolith simulant in the physical validation tests.

3. **Rocket Engine or Equivalent Simulation:** As shown in Figure 8, a 3D-printed nozzle, designed to match the BE-7 engine nozzle, is mounted on the top of the testing chamber to replicate the exhaust characteristics of lunar lander engines. A cold gas thruster is used to expel inert gases at high velocity to simulate the exhaust plume, as they are safer and easier to handle than actual rocket engines. The high-pressure gas supply system shown in Figure 9 is set up to manage the gas flow.

4. **Instrumentation:** As shown in Figure 8, the test chamber is equipped with sensors to measure parameters such as pressure and plume velocity. High-speed cameras and a particle image velocimetry shown in Figure 10 will be used to capture the dynamics of the plume and regolith interaction.



(a) (b)

Figure 10: (a) the Mikrotron EoSens 4.0MCX6 cameras with 566 fps at full 1696x1710 resolution and up to 38,502 fps at reduced resolution, and (b) a Particle Image Velocimetry (PIV) used with the camera to analyze particle movement and plume behavior in the physical validation tests

5. **Data Acquisition Systems:** Advanced data acquisition systems are deployed to manage and analyze the extensive data generated during experiments. This data serves to comprehend PSI effects such as dust ejection, erosion patterns, and potential equipment hazards. Standard DAQ systems can effectively record pressure data measured by sensors within the test chamber. Concurrently, image acquisition hardware interfaces with high-speed cameras to capture and store images depicting the flow field. Subsequently, specialized Particle Image Velocimetry (PIV) software processes these images, extracting valuable velocity information. By correlating tracer particle movement across consecutive frames, this software computes velocity vectors within the flow field. Additionally, specialized image analysis software is employed to track individual particle trajectories over time, allowing for the calculation of particle velocities, trajectories, and other pertinent parameters essential for comprehensive analysis.

By replicating the lunar environment as closely as possible, the testing chamber provides valuable insights into the challenges and effects of PSI, helping to improve the design and safety of future lunar landers.

3.2 Testing Procedure:

We will collaborate with the Department of Physics and Ingram School of Engineering at Texas State University to support lunar missions and seamlessly integrate our experimental payload into their existing testing infrastructure. Throughout the integration and launch phases, utmost attention will be given to ensuring strict compliance with safety protocols and regulatory standards.

In each test session of this investigation, we will commence by evacuating the test chamber to approximately 4 x 10-4 torr. Following this, the plume gas is expelled by the cold gas thruster onto the regolith surface, with an impulse duration of 0.1 second. Subsequently, the plume gas stabilizes into a steady state operation within approximately 60 milliseconds. We meticulously monitor and record the plume's behavior as it interacts with the surface, including variations in velocity, pressure, particle velocities, and trajectories. These tests are designed to be adaptable, allowing for adjustments in nozzle height to explore different configurations.

4 Project Schedule and Milestones:

The following schedule outlines a structured timeline for the project, ensuring that each phase builds on the previous one and leads to the successful completion of the project. Adjustments can be made based on project progress and specific requirements:

Phase 1: Project Planning and Literature Review (Month 1)
- **Milestone 1:** Project Planning and Completion of Literature Review
  - Develop a detailed project plan
  - Review existing research on regolith ejecta and plume-surface interactions
  - Identify knowledge gaps and research questions
- Personnel Costs: $10,000
- **Deliverables:**
  - Project plan
  - Literature review report
  - Research questions and hypotheses

Phase 2: Numerical Simulation Setup (Months 2-3)
- **Milestone 2:** Numerical Model Development
  - Select and set up simulation software (e.g., ANSYS, LAMMPS)
  - Develop numerical models for regolith ejecta
  - Validate models with preliminary data
- Personnel Costs: $20,000
- Software Licenses: $20,000
- Computing Resources: $15,000
- **Deliverables:**
  - Simulation software setup
  - Numerical model documentation

Phase 3: Physical Experiment Design and Setup (Month 4-5)
- **Milestone 3:** Experiment Design Completion
  - Design physical experiments to validate numerical models
  - Procure materials and set up experimental apparatus
- Personnel Costs: $20,000
- Equipment and Materials: $30,000
- Lab Space Rental: $10,000
- **Deliverables:**
  - Experimental design document
  - Experimental setup

Phase 4: Simulation Execution and Data Collection (Month 6-7)
Milestone 4: Simulation and Data Collection Completion
Run numerical simulations
Collect and analyze simulation data
Personnel Costs: $20,000
Deliverables:
Simulation results
Data analysis report

Phase 5: Physical Experiments and Validation (Month 8-9)
Milestone 5: Physical Experiment Execution
Conduct physical experiments
Collect and analyze experimental data
Personnel Costs: $20,000
Equipment and Materials: $30,000
Deliverables:
Experimental results
Comparison report between numerical and experimental data

Phase 6: Data Analysis and Model Refinement (Month 10-11)
Milestone 6: Model Refinement
Compare simulation results with experimental data
Refine numerical models based on experimental validation
Personnel Costs: $20,000
Deliverables:
Refined numerical models
Validation report

Phase 8: Final Report and Presentation (Month 12)
Milestone 8: Project Completion and Presentation
Compile final project report
Prepare and deliver project presentation
Personnel Costs: $10,000
Deliverables:
Final project report
Presentation slides

Budget Overview

- Total Annual Operating Costs: $195,000
  - Personnel Costs: Include salaries for researchers, technicians, and administrative staff.
  - Software Licenses: Cover necessary software tools for simulation and analysis.
  - Computing Resources: Account for high-performance computing needs.
  - Equipment and Materials: Cover costs for physical experiment setups.
  - Lab Space Rental: Include costs for using specialized laboratory facilities.

5 Conclusion:

In the present study, the psi phenomenon associated with the lunar lander's landing process is simulated using Ansys FLUENT. 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. Additionally, testing devices, instruments, and procedures for future physical validation tests are developed. 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. Due to time and cost constraints, the numerical model will be validated and refined through future physical experimental tests. The findings of this research will provide a deeper understanding of plume dynamics, improve predictive capabilities for surface erosion, and enhance the validation of computational models, all of which are essential for advancing the design and planning of future lunar exploration missions.

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