Crater Formation Due to Lunar Plume Impingement

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Introduction

Thruster plume impingement on a surface comprised of small, loose particles may cause blast ejecta to be spread over a large area and possibly cause damage to the vehicle. For this reason it is important to study the effects of plume impingement and crater formation on surfaces like those found on the moon. Lunar soil, also known as regolith, is made up of fine granular particles on the order of 100 microns.[i] Whenever a vehicle lifts-off from such a surface, the exhaust plume from the main engine will cause the formation of a crater. This crater formation may cause laterally ejected mass to be deflected and possibly damage the vehicle.

This study is a first attempt at analyzing the dynamics of crater formation due to thruster exhaust plume impingement during liftoff from the moon. Though soil erosion on the lunar surface is not considered, this study aims at examining the evolution of the shear stress along the lunar surface as the engine fires. The location of the regions of high shear stress will determine where the crater begins to form and will lend insight into how big the crater will be. This information will help determine the probability that something will strike the vehicle. The final sections of this report discuss a novel method for studying this problem that uses a volume of fluid (VOF)[ii] method to track the movement of both the exhaust plume and the eroding surface.

Computational Domain

Since the primary focus of this study was to understand the dynamics of plume impingement during takeoff from the moon, the computational domain is comprised of the engine nozzle and a patch of lunar surface underneath, as seen in Figure 1. Taking advantage of symmetry, the problem was approached from a two dimensional perspective. This allowed for a much lower cell count while still maintaining high resolution where necessary. Total cell count was 61,800. Though this is a rather low cell count by today's standards, the time-step had to be kept rather low ($1x10^{-5}$ s.) in order to capture the high velocity exhaust coming out of the nozzle. This produced run times on the order of 5 hours.

Since it was important to resolve the plume expansion as it left the nozzle, grid resolution was increased near the nozzle wall yielding a Y+ value between 1 and 5. This ensures proper resolution of the viscous boundary layer. Since the problem focuses on the interaction with the lunar surface, a rather high resolution must also be employed at the second wall boundary (far right).

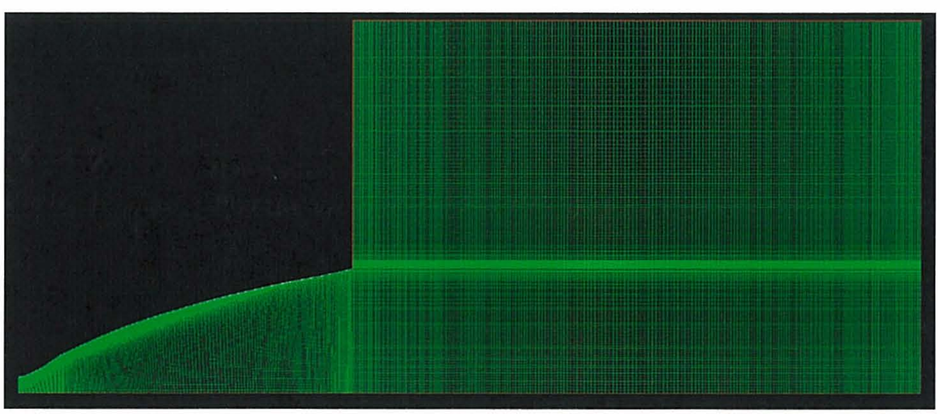


Figure 1

Boundary Conditions

Taking advantage of the symmetry present in the problem, an axisymmetric, two dimensional grid was employed. Since the thrusters for a future lunar lander have not yet been designed, a nominal value of 1.76 MPa and 3500K was used as a pressure inlet boundary condition at the throat of the engine. The nozzle wall (bell shaped boundary) as well as the lunar surface (far right boundary) were both modeled using a no slip wall boundary condition. The boundaries at the top and directly above the nozzle exit were modeled using a pressure outlet boundary condition that held the ambient pressure at 1 Pa. This was a necessary assumption for the continuum based solver to function properly. The ambient temperature was set at 300K, and the gravitational acceleration was set to 1.622 m/s^2 (0.17 g).

Solver

Due to the low backpressure and high velocities, a density based solver was employed. The density based solver in ANSYS FLUENT is a very robust solver that is applicable to many different problems. The implicit formulation of this solver makes it even more robust especially when dealing with large gradients. The turbulence model used in this study was the Spalart Allmaras one equation model with vorticity based turbulence production. Both the fluid and turbulence equations use a second order upwind scheme, while temporal accuracy was maintained at first order.

Results

Figure 2. illustrates the time accurate results from the simulation. Beginning at the top, each frame is made up of four quadrants. The top left quadrant is a plot of the velocity magnitude, in meters per second. The top right quadrant is a line plot (green) of the pressure along the lunar surface, in Pascal. The bottom left quadrant shows the line plot (blue) of the shear stress along the lunar surface, in Pascal. Finally, the lower right quadrant is a plot of the temperature in Kelvin. The elapsed time is shown at the bottom of each frame and ranges from 7.30 $x10^{-4}$ to 1.93 $x10^{-3}$. Figure 2. consists of a total of three frames.

These plots illustrate a wealth of interesting physics. The first notable feature is the clear distinction of the shock wave as it moves toward the surface. The plume expansion in the 1 Pa. environment is evident from the beginning. As it impinges on the surface, an area of high temperature and low velocity develops at the stagnation region directly below the nozzle. The shock then bounces back upstream toward the nozzle. Further from the stagnation region (around 0.6 m away), the shock reattaches to the ground. This is seen as a spike in pressure and shear stress along the lunar surface.

Another interesting feature is the development of a recirculation region just behind the shock. This is best seen in the shear stress plot. As expected, the shock reattachment point shows a peak in the pressure and shear stress, but just behind the shock there is a region of negative shear stress. This indicates that the exhaust plume has a recirculation region just behind the shock reattachment point. The recirculation region can also be seen in the vector plot shown in Figure 3.

Extending radially past the shock reattachment location, there is a steady decrease in the pressure and shear stress. This is an effect of the plume dissipation into the vacuum found on the moon. It is in this region where the flow is allowed to pick up speed and be accelerated by the main exhaust flow and bouncing shocks.

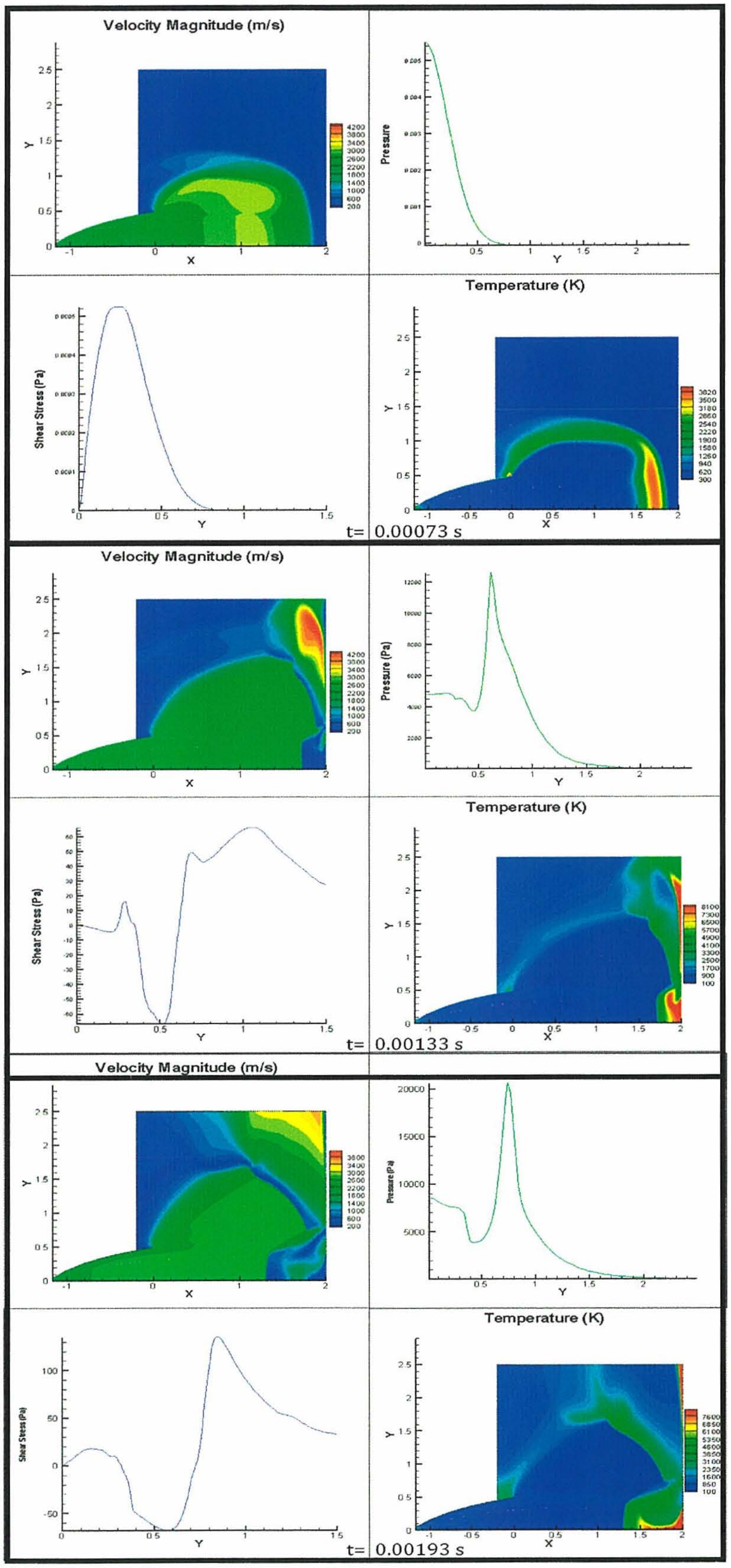

Velocity Magnitude (m/s)
Pressure
Shear Stress (Pa)
Temperature (K)
t= 0.00073 s
Velocity Magnitude (m/s)
Pressure (Pa)
Shear Stress (Pa)
Temperature (K)
t= 0.00133 s
Velocity Magnitude (m/s)
Pressure (Pa)
Shear Stress (Pa)
Temperature (K)
t= 0.00193 s

Figure 2

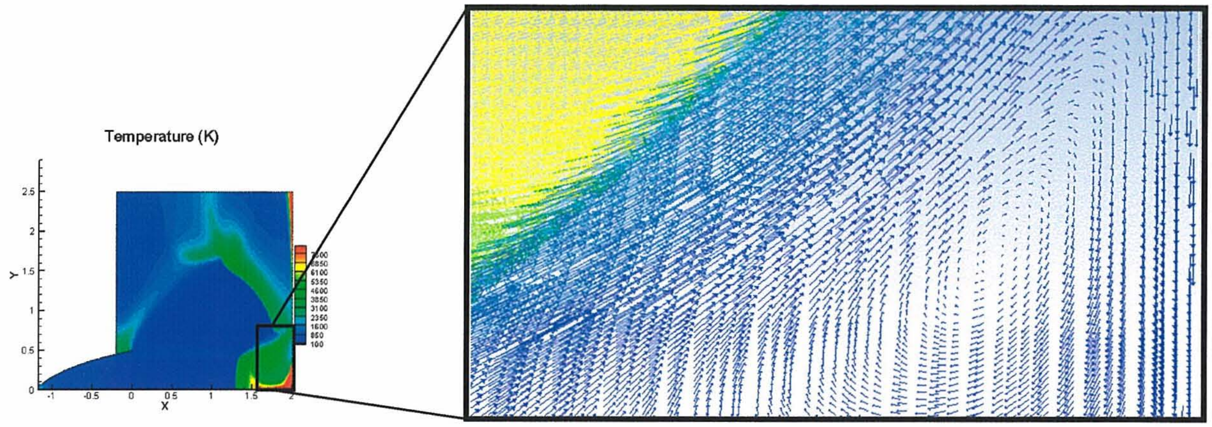


Figure 3

The shock reattachment point and recirculation region are not merely interesting physical phenomena. They play into how the crater will be formed. Comparing the plots from frame three to those from frame six it is clear that the shock moves outward. As the shock reattachment point moves away from the nozzle, the area of high pressure and shear stress will act as a front that essentially scoops away regolith to form the crater. The recirculation region also helps with crater formation by digging into the regolith therefore making the crater deeper.

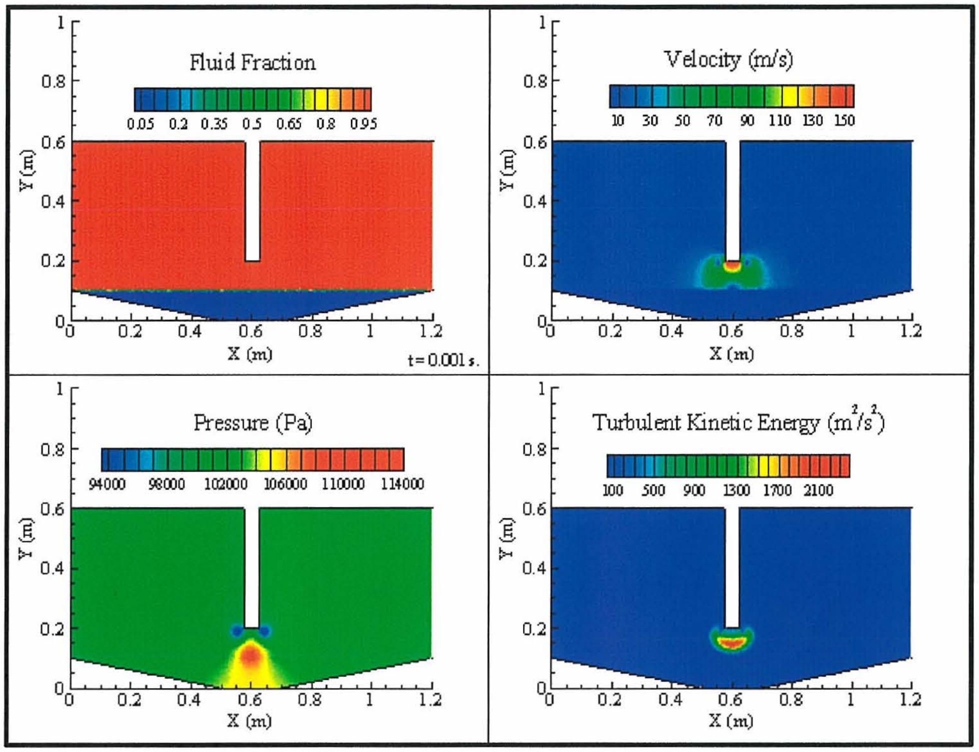
Since this study does not allow for wall deformation, it is difficult to say how deep this plume would dig into the surface. It does show however, that these plume impingements can cause some large pressure, temperature, and shear stress gradients that must be taken into account when designing any vehicle that is to take off from the moon, mars, or any other surface made up of loose particles.

Using the VOF method to study plume impingement

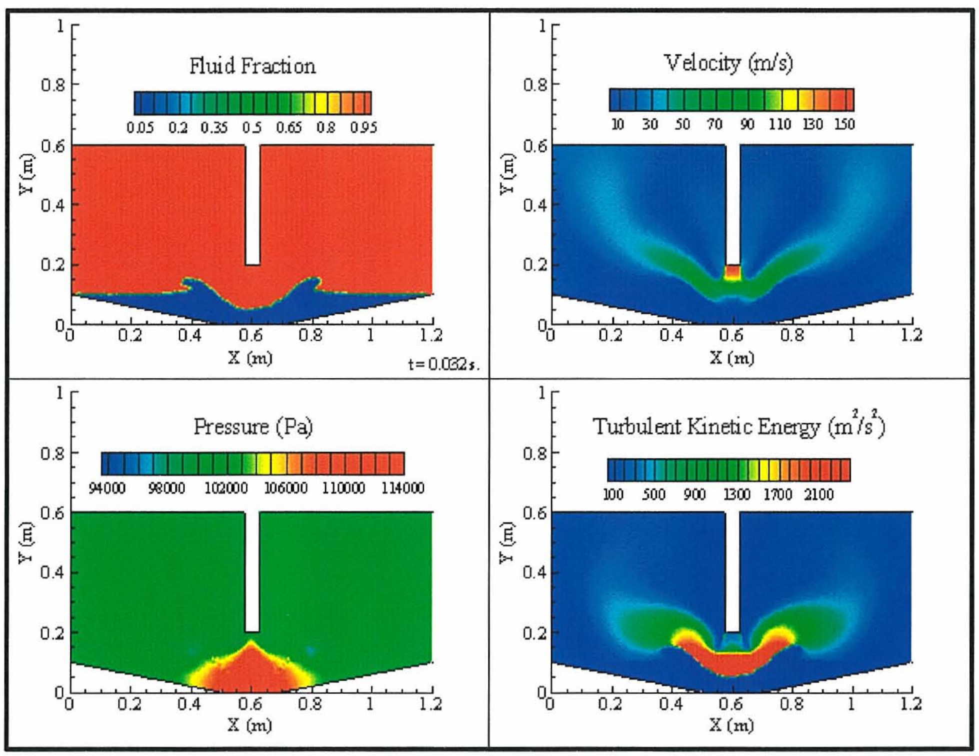
The final part of this study attempted to incorporate the deforming surface in the plume impingement model. This method took a different approach and used the Volume of Fluid (VOF) method to treat the plume exhaust and regolith surface as two different fluids. Though granular surfaces don't follow the same physics described by the Navier-Stokes fluid equations, treating it as a fluid will allow the energy from the main exhaust flow to reshape the surface and cause a similar surface deflection. For this proof of concept simulation, the dense fluid representing the regolith is water.

The results of this simulation are shown in Figure 4. The six frames are comprised of four quadrants each. The top left shows a plot of the VOF quantity. This is simply the contour created by the interface between the water and air. The top right plot shows the velocity magnitude of both fluids. The bottom left quadrant is a plot of the pressure contours, and the bottom right quadrant is a plot of the turbulent kinetic energy. This last plot is used to visualize areas of high turbulence and shear.

The VOF plots show that the impinging exhaust jet causes the regolith simulant fluid to be displaced. As the regolith simulant fluid is formed into a crater-like shape, the velocity magnitude plots show that the exhaust jet gets deflected from initially spreading radially outward, to spreading almost vertically up toward the nozzle. This is precisely why it is important to calculate the magnitude of this deflection. If the scenario depicted in this proof of concept run was to happen to a real spacecraft, the exhaust deflection would cause high velocity particles to impact the bottom of the spacecraft and possibly cause damage.



Fluid Fraction
0.05 0.2 0.35 0.5 0.65 0.8 0.95
Velocity (m/s)
10 30 50 70 90 110 130 150
Pressure (Pa)
94000 98000 102000 106000 110000 114000
Turbulent Kinetic Energy (m²/s²)
100 500 900 1300 1700 2100
Y (m)
X (m)
t=0.001 s.



Fluid Fraction
0.05 0.2 0.35 0.5 0.65 0.8 0.95
Velocity (m/s)
10 30 50 70 90 110 130 150
Pressure (Pa)
94000 98000 102000 106000 110000 114000
Turbulent Kinetic Energy (m²/s²)
100 500 900 1300 1700 2100
Y (m)
X (m)
t=0.032 s.

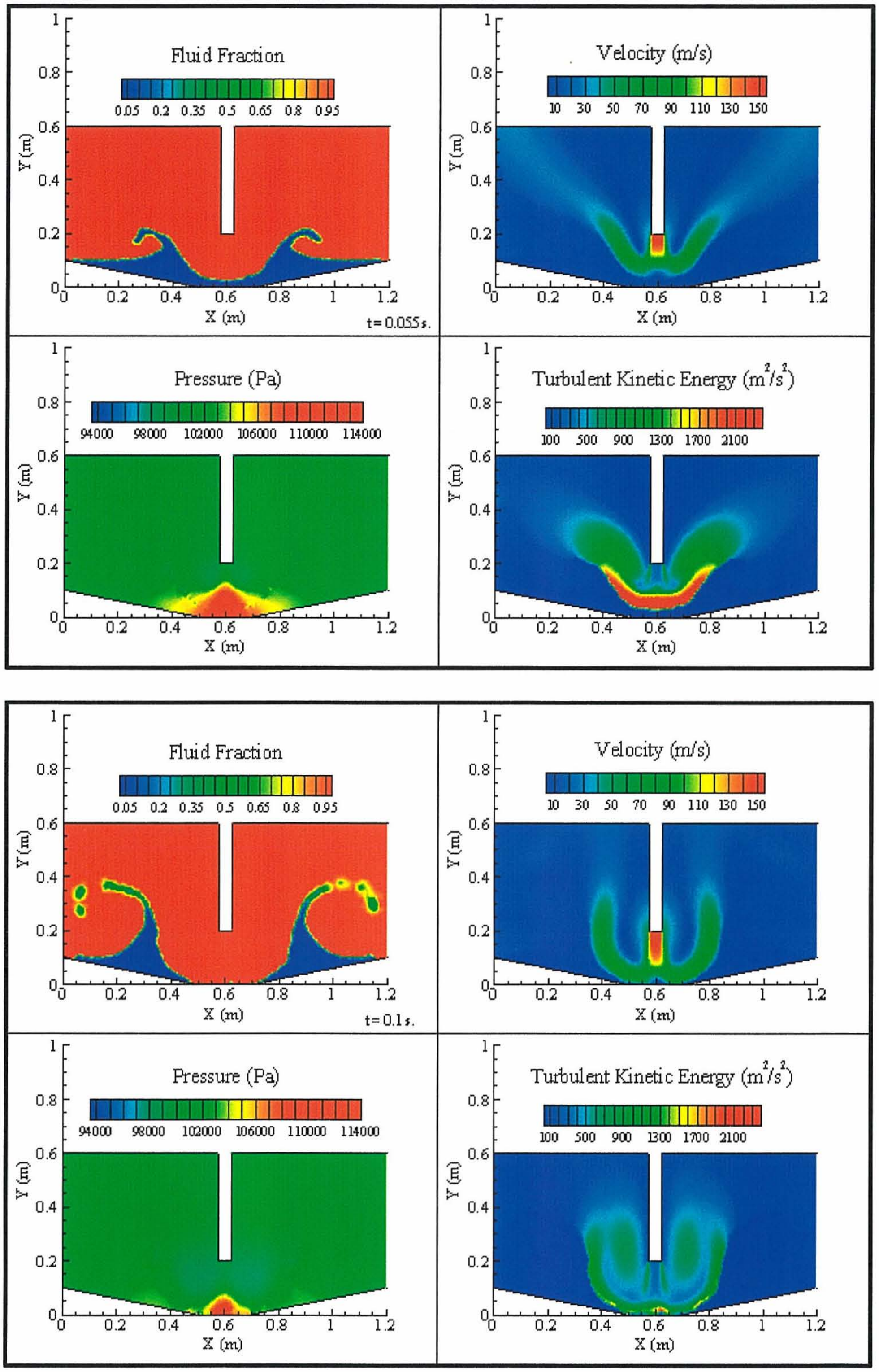


Figure 4

This proof of concept run uses water as the regolith simulant fluid. Future studies will attempt to change the fluid properties to more closely match those of lunar regolith. By doing this it will be possible to better estimate the depth of the crater and design a system that will minimize the risk of having regolith particles impact the vehicle upon takeoff.

Conclusion

By using two different CFD methods, the dynamics of crater formation upon rocket nozzle exhaust plume impingement were studied. The first method showed that the shock reattachment point and recirculation region play a critical part in "digging the crater". Even on a surface with no backpressure (like the moon), the risk of digging a large crater remains. The second method showed that the VOF technique may be a viable option for estimating the crater height and, in turn, determining the risk of particle impact on the vehicle.

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[i] Phillip Metzger, Xiaoyi Li, Christopher D. Immer, John E. Lane. *ISRU Implications for Lunar and Martian Plume Effects.* 47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition, Orlando, Florida, Jan. 5-8, 2009

[ii] ANSYS FLUENT Users Guide