**UNDERSTANDING THE SURFACE MODIFICATIONS AT LANDING SITE DUE TO SPACECRAFT (SOFT) LANDING ON THE MOON** Sanjeev Kumar Mishra and K. Durga Prasad*, Physical Research Laboratory, Ahmedabad 380009, India (*durgaprasad@prl.res.in)

**Introduction:** Understanding surface modifications at landing site during spacecraft landing on planetary surfaces is important for planetary missions from scientific as well as engineering perspectives. The bulk properties of the landing site, especially the upper layer of its regolith, and its physical interaction with the supersonic jet plumes principally determines the possible modifications to the surface. The resulted cratering and consequently ejected particle kinematics provide clues to the physical affects that might have caused to its surroundings. Also, for carrying out in situ measurements, it is important to know beforehand the extent to which the landing site might get altered by the jet plumes. This information is also necessary for planning and properly interpreting the science data from in situ experiments. Only successful lunar landings were those of Luna and Apollo missions that were carried out nearly 4 decades ago until the recent landing of Chang'e 3 [1]. India's second mission to Moon, Chandrayaan-2, also plans to land on lunar surface. Several such missions might also follow in near future. In this context, understanding the disturbance caused to the surface due to spacecraft landings gains prominence. Therefore, an effort has been made to numerically investigate the plume/soil dynamics and affects of jet impingement on the lunar surface. Preliminary results are presented.

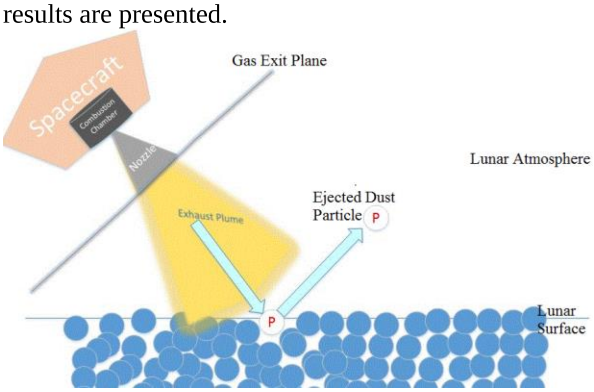


*Figure 1. Schematic showing particle level plume/ surface interaction (particle dimensions are exaggerated)*

**Physics of Plume/Soil Interaction and Cratering Mechanisms:** The rocket exhaust plume coming out of the nozzle exit strikes the lunar surface with an impingement pressure which is dependent on the jet expansion ratio (e), a ratio of exhaust plume pressure at the nozzle exit to that on the planetary atmosphere/surface [2]. As shown in Fig. 1, the plume strikes the surface particles directing them up into lunar atmosphere. The momentum carried out by the diffused gases will also be transferred to the ejected particles (not shown in schematic).

The primary modification caused to the surface due to landing is the formation of a crater/pit. The crater formation theories were studied in great detail during Apollo and Viking Missions. Three different cratering mechanisms were predicted - *viscous erosion*, *diffused gas eruption* [3], and *bearing capacity failure* [4]. The dominant mechanisms in the case of lunar surface are viscous and diffused gas erosions due to a comparatively high relative density and shear strength of the soil. Bearing capacity failure can be expected for landing sites having a comparatively low relative densities and sheer strength than the Apollo sites [5].

The effects of exhaust plume on lunar surface and the consequent surface modifications have been studied by Metzger et al [6] and modified Robert's theory [7]. The pit formation due to high velocity rocket exhaust plumes is also demonstrated experimentally. Mehta et al [2] made a more elaborate effort to investigate the plume flow fields and the cratering mechanisms caused by jet impingement. Morris et al [8] used a loosely coupled continuum DSMC solver to simulate the interaction between the exhaust from a rocket engine with the lunar surface. Both the dust trajectories and the flow fields were computed for various hovering altitudes and dust grain sizes [2].

In the present study, the process of pit formation, its dimensions i.e. depth, volume and area as a function of average grain size, hardness of the dust particles and the ejected dust velocity and mass flux density are derived to understand the surface modifications during lunar landings.

**Methodology:** The numerical calculations based on Sheldon-Kanhare eqn [9] were carried out using MATLAB. The Lunar regolith is assumed to have constant hardness throughout.

$$V=K_D v^3 D^3 \sigma^{3/2} H_v^{-3/2} \quad (1)$$

The volume of pit caused by one impinging particle is calculated using equation (1) (see [6]).

$$dm/dt = 2(\tau - \tau_c)/(a.u) \quad (2)$$

Mass flux density was calculated using eqn (2) (see [3]). The various parameters used and their typical values used for these calculations are listed in Table 1. The variation of pit depth, area and volume as a function of the grain size and vicker's hardness [11] of the particles were calculated.

| Parameter | Value |
|---|---|
| Dust particle diameter (D) | $50*10^{-6}$ m |
| Engine thrust (F) | 1600 N |
| Dust particle density (σ) | 3500 kg-m$^{-3}$ |
| Combustion chamber (see fig. 1) viscosity ($\mu_c$) | 12 N-s-m$^{-2}$ |
| Combustion chamber temperature ($T_c$) | 3500 K |
| Mach number at exit plane (see fig. 1) | 5 |
| Drag coefficient ($C_d$) | 0.2 |
| Cohessive stress of soil (c) | 100 Pa |
| Diameter of the nozzle | 0.2 m |
| Friction angle | 30 degree |
| Sheer stress caused by the plume at the boundary layer | 10000 Pa |
| Exit plane gas velocity | 3500 ms$^{-1}$ |

*Table 1. Parameters used for calculations [10]*

**Results and Discussion:** The calculations were carried out for various grain sizes and particle hardness. However, results for only one typical case is presented here. For a landing site with typical average Vicker's hardness, $H_v = 50$, with the lander hovering vertically at a height of 15 m for 5 seconds, an amount of ~8×10$^5$ cm$^3$ of dust will be lofted up which will result into an equivalent pit of dimensions 1m×1m×0.8 m. It has been found that the hovering altitude has a negligible effect on overall pit volume because of the absence of atmosphere on lunar surface, however, hovering time duration has a significant effect on the overall pit size. The eject velocity as a function of grain size is shown in figure 2 and it has been found that micron size particles can attain eject velocities of ~ 3500 m/s. For large particles with size more than 1 mm, the eject velocity was found to decrease monotonically. The mass flux density for particles with grain sizes in the range of microns is found to be 5.5× 10$^{-2}$ g/(cm$^2$-s) as indicated in figure 3.

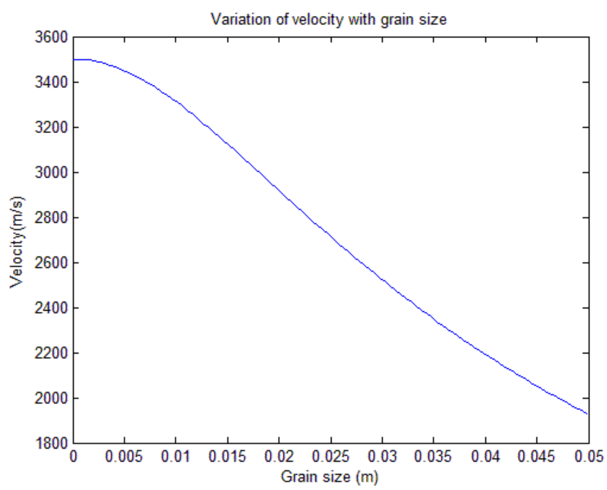


*Figure 2. Variation of Dust Particle Eject Velocity with Average Particle Grain Size*

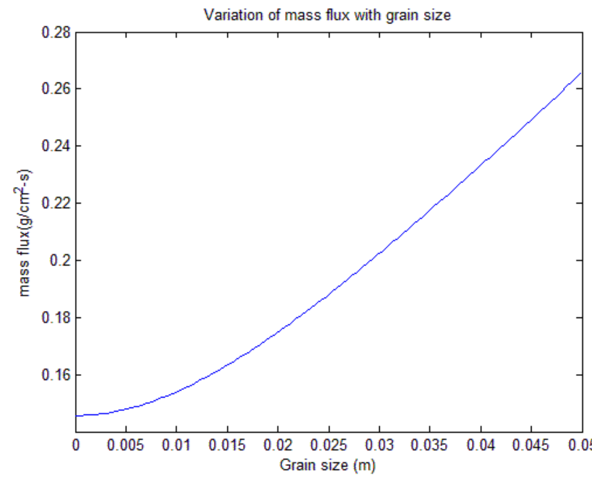


*Figure 3. Variation of Mass Flux Density with Average Particle Grain Size*

**Summary:** Surface modifications due to spacecraft landing on lunar surface was studied and preliminary results were presented. The extent of modification was found to be a function of hovering time. Variation of dust eject velocity and its mass flux density as a function of grain size was also obtained for the simplest case. The pit profile, i.e. depth, area and volume as a function of particle hardness were also obtained. Most of the results obtained are based on simplest possible formulation of lunar aerodynamics. Further work is needed to account for the assumptions close to realistic conditions which would consequently enhance our understanding of surface modifications during spacecraft landing on lunar surface.

**References:** [1] Li, C., Liu, J., Ren, X. et al. (2015) SSR, 190: 85. doi:10.1007/s11214-014-0134-7 [2] Mehta et al (2010), 41st LPSC, pp. 2350. [3] Scott et al (1968), AIAA Journal 6(2), 258-64. [4] Alexander et al (1966), NAS9-4825, AL [5] Metzger P.T. (2009), JAE Vol. 21, No. 1, pp. 24-32 [6] Metzger P.T. (2008) ASCE, Long Beach, CA, p1. [7] Roberts, Leonard (1963), NY, 63-50. [8] Morris et al (2011), AIPCP, Vol. 1333, Issue 1 [9] Sheldon and Kanhere (1972), *Wear* 21, 195-209. [10] *Lunar Sourcebook* (1991), Grant H. Heiken et al, Cambridge Univ. Press, ISBN: 0-521-33444-6 [11] Doug Rickman et al (2008), AIPCP, Vol. 969, Issue 1