EPJ Web of Conferences **340**, 06007 (2025) https://doi.org/10.1051/epjconf/202534006007
Powders & Grains 2025

Thrust analysis of rocket landing on planetary granular surfaces

Prasad Ranganath Sonar[1,2,*] and *Hiroaki* Katsuragi[1,**]

[1]Department of Earth and Space Science, Osaka University, 1-1 Machikaneyama, Toyonaka, Osaka, Japan, 560 0043.
[2]Present address: Food Engineering Department, CSIR-Central Food Technological Research Institute, Mysuru, India, 570 020.

Abstract. We systematically investigate the thrust exerted by a high-speed air jet using laboratory experiments. The study considers smooth and bumpy rigid plates, as well as a deformable granular bed that simulates planetary surfaces. A vertically downward, pressure-controlled air jet (0.01–0.3 MPa) is emitted through nozzles of varying diameters (d_n), with the nozzle-to-surface distance (h_n) adjusted to mimic the rocket's descent. For non-deformable surfaces, thrust (T_n) increases with jet velocity (v_n), with smoother surfaces generating maximum thrust and finer grains producing greater thrust than coarser ones. At high v_n, increasing h_n enhances T_n, while its effect diminishes at lower velocities. For deformable granular beds, T_n decreases with increasing grain size (d_g), and h_n has minimal influence when erosion occurs. Narrower nozzles produce higher T_n for a constant h_n. These findings provide critical insights into optimizing thrust and landing conditions for rocket descents on diverse planetary surfaces.

1 Introduction

The ambition to establish a human presence on the Moon requires overcoming significant technical challenges, with safe landing mechanisms being a top priority [1, 2]. Developing sustainable and secure landing systems will open vast opportunities for future space exploration. A key hurdle in space colonization is achieving stable landings on planetary surfaces, where the interaction between a lander's exhaust and the surface plays a crucial role [3, 4]. As the rocket thrust interacts with the surface, it often displaces dust or soil. This interaction can create craters, dust clouds, and erosion of the surface, which further complicates the landing process. Understanding these plume-surface interactions is one of the most pressing issues in space engineering [5].

During the landing phase, rockets generally utilize a "powered descent", where the engines produce adjustable thrust to decelerate the vehicle as it nears the surface. This thrust must be carefully controlled to ensure a soft landing without generating excessive impact forces. On planetary bodies with weaker gravity, such as the Moon, the required thrust is lower than on Earth, but the challenge shifts toward managing descent speed and maintaining orientation. A critical aspect of powered descent on granular surfaces is understanding how thrust varies as the lander nears the terrain. Our study investigates thrust behavior near granular surfaces to optimize landing strategies for future planetary missions.

2 Experiments

We systematically conduct lab-scale experiments to measure the thrust exerted by a high-speed air jet. Figure 1(a) illustrates the schematic of our experimental setup. The tests are performed over non-deformable smooth (S) and bumpy (B) rigid plates, along with deformable granular beds consisting of grain density, ρ_g, and grain diameter, d_g, which serves as a planetary surface simulant (see Tab. 1 and Fig. 1(b)). To create bumpy granular beds of different types, grains of the desired sizes are glued to a flat surface. Table 1 presents the various types of beds used in this study. We perform the experiments under atmospheric conditions (no vacuum). A compressed air jet, representing the rocket's nozzle exhaust, is directed vertically downward. The pressure-controlled air jet, with a pressure range of 0.01 – 0.3 MPa, is emitted through a nozzle. We vary the nozzle diameter, d_n, to control the jet velocity, v_n. Additionally, the distance between the nozzle tip and the granular surface, h_n, is adjusted to simulate the dynamic descent of the rocket as it approaches the landing surface. Table 2 lists the range of input parameters. The thrust, T_n, is estimated by averaging the measurements from three load cells positioned beneath the rigid plates or containers holding the granular simulant. For deformable granular beds, the bed thickness was kept constant at 70 mm for all experiments. As demonstrated in our previous study [6], this thickness is sufficient to ensure that the crater shape remains unaffected across a range of air jet conditions. Therefore, we consider its influence on the thrust measurements to be negligible. Experimental and parametric details are provided in Sonar *et. al* [6].

---

[*] e-mail: prasadrsonar@gmail.com
[**] e-mail: katsuragi@ess.sci.osaka-u.ac.jp

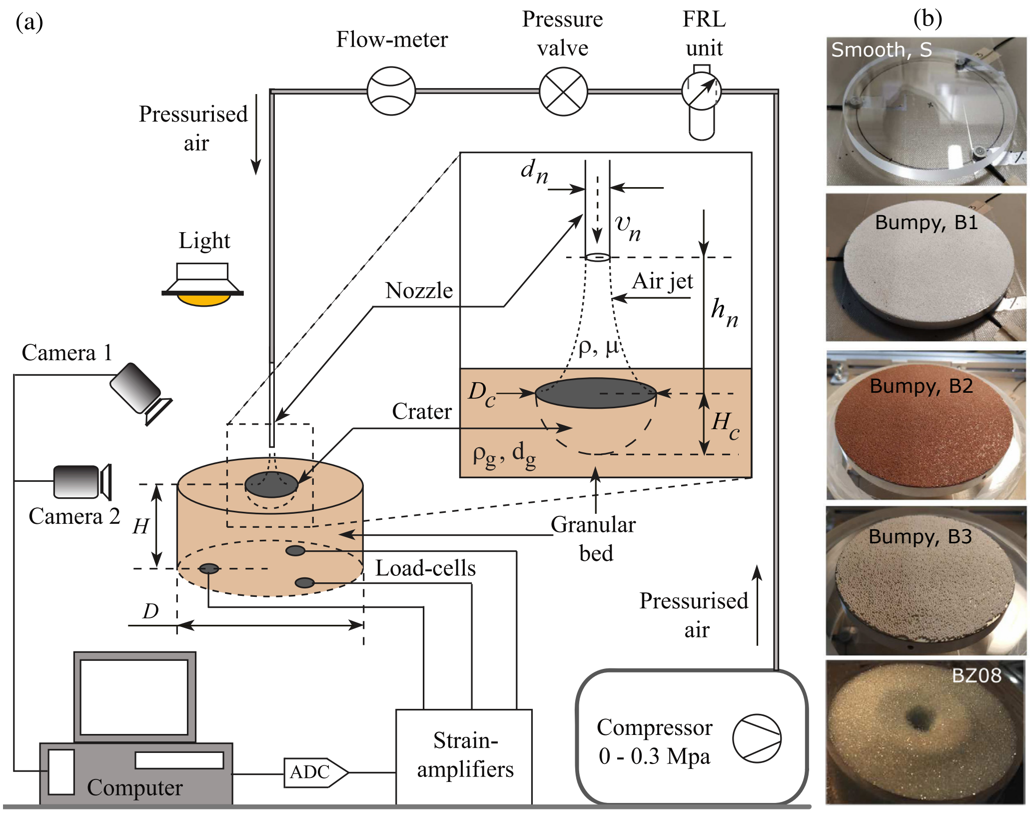

Figure 1. (a) Air-jet impact experiments in a 3D setup. (b) Bed conditions: non-deformable smooth (S), bumpy (B1-100 μm, B2-500 μm, B3-1 mm), and deformable (BZ08-800 μm, BZ2-2 mm).

Table 1. Properties of bed surfaces.

Bed surface	Label	Grain size, d_g (μm)
1. Non-deformable, smooth	S	0
2. Non-deformable, bumpy	B1	100
3. Non-deformable, bumpy	B2	500
4. Non-deformable, bumpy	B3	1000
5. Deformable, granular	BZ08	0.71-0.99
6. Deformable, granular	BZ2	1.50-2.50

Table 2. Operational range of control parameters.

Parameters	Operational range
1. Air jet velocity, v_n	19 to 375 m/s
2. Nozzle diameter, d_n	2 to 6 mm
3. Nozzle height, h_n	10 to 200 mm
4. Grain's diameter, d_g	0.1 to 2.5 mm
5. Grain's density, ρ_g	2.6 g/cm^3
6. Grain's shape	spherical

3 Results and discussion

The thrust (T_n) generated by an impinging air jet is influenced by several factors, including jet velocity (v_n), nozzle height (h_n), surface roughness, and nozzle diameter (d_n). Figure 2(a) shows that the thrust force increases with increasing jet velocity, while the linear relationship between T_n and v_n is evident in Fig. 2(b). The plot presented corresponds to a nozzle diameter of d_n = 3.6 mm and a nozzle height of h_n = 20 mm, using BZ2 as the granular medium. This trend is consistent across both deformable and non-deformable granular bed conditions.

To investigate the effect of surface roughness, we compared thrust forces generated when the air jet impacts non-deformable bed conditions, specifically fixed beds with varying roughness. As shown in Fig. 2(c), at the same jet velocity, smoother base surfaces produce significantly higher thrust compared to rough and bumpy surfaces. This difference is likely due to the formation of a stable boundary layer on smooth surfaces, which facilitates radial airflow with minimal disturbance. Such smooth radial outflow enhances vertical momentum transfer and reduces turbulence-induced energy dissipation. In contrast, rough or bumpy surfaces disturb the boundary layer, promote lateral momentum dispersion through turbulence, and reduce the effective vertical force measured as thrust. This behavior is more pronounced at higher velocities, while at lower velocities the thrust remains relatively unchanged between smooth and rough surfaces.

Increasing the nozzle height (h_n) enhances the jet's coverage area, promoting a more uniform force distribution and improving thrust, especially at higher velocities (see Fig. 2(d)). However, at lower velocities, the effect of h_n is minimal, since the jet momentum is not sufficient to have a significant impact. The data presented corresponds to the bed condition B1 using d_n = 3.6 mm, and a similar behavior is observed for other base configurations. Figure 2(e) illustrates the thrust generated under three different velocity conditions, using a nozzle diameter of d_n = 2 mm

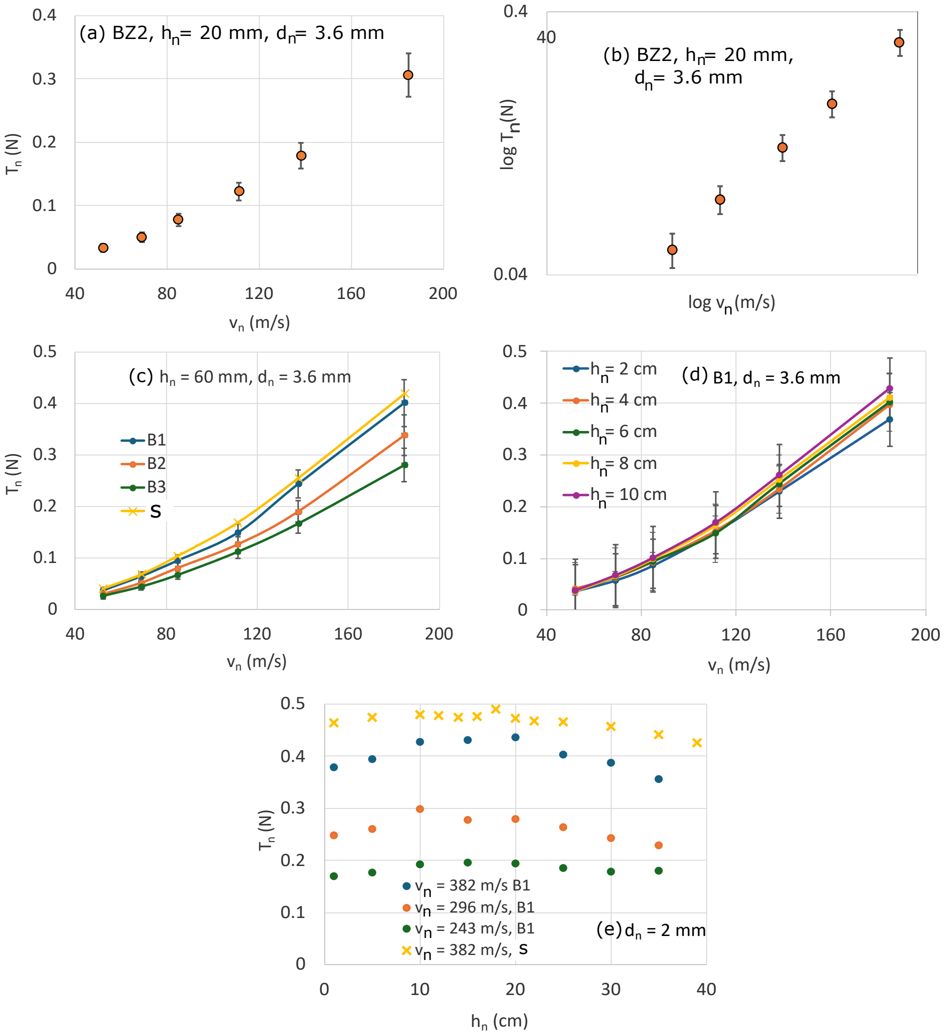

Figure 2. Thrust generated by air-jet impact on (a-b) deformable surface for various v_n conditions, and (c), (d), (e) non-deformable bed surfaces for various surfaces, h_n, and v_n conditions, respectively.

for both smooth and B1 beds. The results show that thrust increases as h_n increases to a critical height, after which it decreases with further increases in h_n. This indicates that maximum thrust is achieved at a nozzle height between 150 mm and 200 mm for both smooth and rough surfaces. In summary, smooth surfaces yield higher thrust, emphasizing the need to optimize surface smoothness, nozzle diameter, and height for maximum jet performance.

Accurate thrust measurement becomes challenging when dealing with highly deformable beds due to limitations in the experimental setup. As shown in Fig. 3(a), using fine grains (BZ08), significant bed deformation results in large material flow into the air, reducing the system's mass on the load cells and causing errors in thrust measurement. These errors become prominent in highly deformable beds and deeper craters, while shallow (scissor-shaped) craters or larger grains (e.g., BZ2) produce more reliable thrust data, as the grains primarily move over the bed surface. For instance, employing a wider nozzle diameter that generates lower-velocity air jets shows consistent results with Fig. 3(b), where thrust increases with h_n, particularly at higher velocities, despite the formation of craters. Figure 3(c) compares thrust forces across different bed conditions at various velocities. While the flat smooth base consistently produces the maximum thrust, an interesting observation emerges. In some cases, deformable beds generate higher thrust than non-deformable conditions, particularly at low h_n values where measurement errors are minimized.

Finally, Fig. 3(d) examines the relationship between thrust force and the erosion number $E_c = Sh\,(d_n/h_n)$, where Shield's number $Sh = (v_n/\sqrt{gd_g})\,\sqrt{\rho_a/(\rho_g-\rho_a)}$ that incorporates various relevant parameters like air density, ρ_a, and gravitational constant, g [7, 8]. However, in our previous study [6], we found that the scaling parameter Sh was insufficient to describe the crater shape, primarily because it does not account for the nozzle height, h_n. In contrast, although E_c significantly influenced the crater morphology, the current results indicate that the thrust force is independent of E_c. Identifying a suitable scaling parameter that governs thrust forces during crater formation remains an open challenge and motivation for future research.

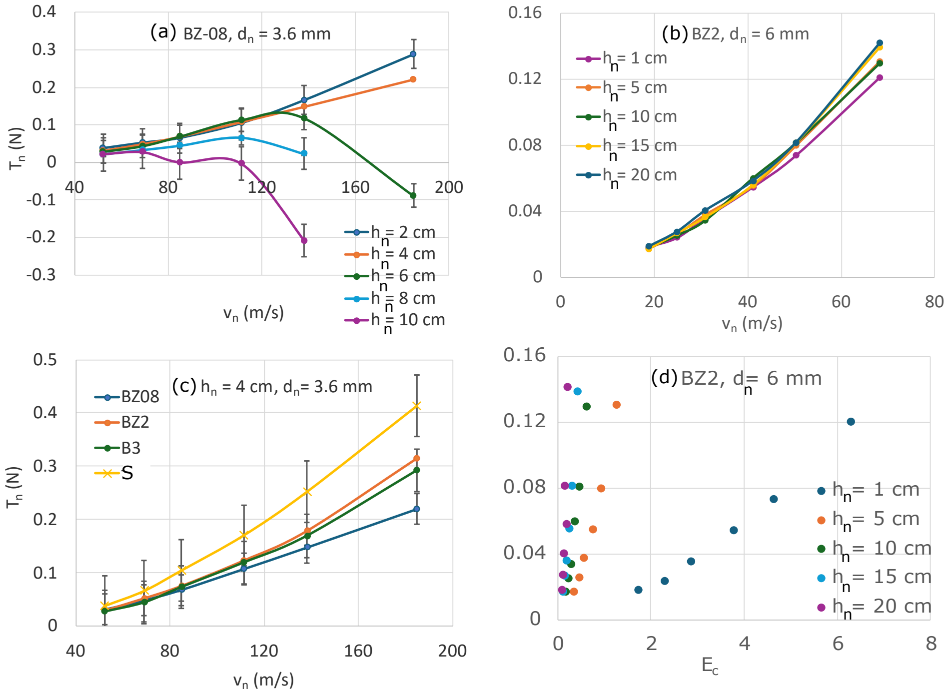

Figure 3. Thrust generated by air-jet impact on various deformable bed surfaces to study the effect of (a) v_n, (b) h_n, (c) bed surface, and (d) E_c.

4 Conclusion

The study demonstrates that thrust generation in an impinging air jet system is influenced by jet velocity, nozzle height, surface roughness, and nozzle diameter. Higher velocities and smoother surfaces enhance thrust by stabilizing airflow, while rough surfaces and low velocities reduce it. Nozzle height significantly affects thrust at higher velocities, with optimal performance at a critical height. Additionally, larger nozzle diameters improve thrust at low velocities. Despite challenges in measuring thrust for highly deformable beds, the study reveals that deformable surfaces can sometimes generate higher thrust than non-deformable ones. Identifying a suitable scaling parameter for thrust prediction during crater formation remains a key focus for future research.

Funding. This work was supported by the JSPS KAKENHI, Grant No. JP18H03679 and JP24H00196, and JSPS-DST Bilateral Program, Grant No. JPSJBP120227710.

References

[1] P.T. Metzger, Erosion rate of lunar soil under a landing rocket, part 1: Identifying the rate-limiting physics, Icarus **417**, 116136 (2024). https://doi.org/10.1016/j.icarus.2024.116136

[2] P.T. Metzger, Erosion rate of lunar soil under a landing rocket, part 2: Benchmarking and predictions, Icarus **417**, 116135 (2024). https://doi.org/10.1016/j.icarus.2024.116135

[3] J. Capecelatro, Modeling high-speed gas–particle flows relevant to spacecraft landings, Int. J. Multiphase Flow **150**, 104008 (2022). https://doi.org/10.1016/j.ijmultiphaseflow.2022.104008

[4] S.K. Mishra, K.D. Prasad, Numerical evaluation of surface modifications at landing site due to spacecraft (soft) landing on the moon, Planet. Space Sci. **156**, 57 (2018). https://doi.org/10.1016/j.pss.2018.03.005

[5] M.T. Gorman, J.S. Rubio, M.X. Diaz-Lopez, W.A. Chambers, A.M. Korzun, J. Rabinovitch, R. Ni, Scaling laws of plume-induced granular cratering, PNAS Nexus **2**, pgad300 (2023). https://doi.org/10.1093/pnasnexus/pgad300

[6] P. Sonar, H. Katsuragi, Air-jet impact craters on granular surfaces: a universal scaling, J. Fluid Mech. **998**, A29 (2024). https://doi.org/10.1017/jfm.2024.906

[7] N. Rajaratnam, S. Beltaos, Erosion by impinging circular turbulent jets, J. Hydraul. Div. **103**, 1191 (1977). https://doi.org/10.1061/JYCEAJ.0004852

[8] C.M. Donohue, P.T. Metzger, C.D. Immer, Empiri- cal scaling laws of rocket exhaust cratering, arXiv preprint arXiv:2104.05176 (2021). https://doi.org/10.48550/arXiv.2104.05176