

A review on Deflector Cones Geometrical Characteristics for Lunar Landing Pads

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Abstract

This work emphasizes the impacts of undergraduate summer research in developing life-long learning critical to engineering education. The research topic is associated with space exploration, which involves using and developing state-of-the-art science knowledge and technology highly relevant to engineering. Specifically, the research project analyzes the geometric characteristics of deflector cones on landing pads to enhance safety and minimize surface erosion during lunar landing. The research study was conducted by a second-year engineering student under the supervision of an engineering professor. The research experience provided the student the opportunity to work with real-world applications, develop numerical codes for data analysis, cultivate self-learning of new topics through literature review, generate graphical representations of physical phenomena related to lunar landing, and creatively solve difficult problems using an engineering approach. This project has strengthened core engineering skills that are essential for undergraduate and graduate education, and a future career in mechanical engineering and design. Sharing these findings highlights the potential for early-stage research to contribute meaningfully to space exploration and innovation while effectively advancing STEM education and experiences at the college level.

Introduction

Experiential learning opportunities that bridge the gap between classroom theory and real-world application are essential for fostering effective education for a student of any discipline. In a study by Alfaro [1], real-world experiences provide students with invaluable experiences through hands-on projects that are not associated with a letter grade. This can foster skills in creative problem-solving, communication, efficient design processes, and an overall sense of commitment to something real and impactful. Similarly, an undergraduate engineering student's summer research reflects the significance of equipping education beyond the classroom, integrating methods such as literature review, programming, analyzing, and forming graphics. The undergraduate engineering research student referenced in this paper is one of the authors recounting their personal experiences and evaluating the educational benefits gained through the research process.

The primary objective of this research is to determine optimal geometric characteristics and design features of deflector cones to improve the safety, efficiency, and economic feasibility of lunar rocket landings. This topic becomes increasingly more important as moon missions become more popular with internationally represented moon bases dedicated to lunar and space research. Currently, rockets land on the bare lunar surface, which chaotically blows particles and debris, creating hazardous scenarios for these future lunar facilities, equipment, and personnel. Flat landing pads have been considered to mitigate this issue, but they are susceptible to rapid erosion due to the high pressure and temperature acting normally on the pad. Additionally, these flat pads deflect acoustic loads and shock effects back onto the rocket decreasing its safety. The utilization of deflector cones is an innovation that will be revolutionary in combating these concerns. Deflector cones, placed beneath the rocket landing zones, propose to strengthen the efficiency, economics, and safety of lunar landings.

The research process has included the literature review of several related research articles involving deflector cones and their effectiveness in diverging pressure, temperature, and acoustic loads, leading to a much slower rate of erosion. By evaluating geometric variables and their relationship with deflector effectiveness in literature scenarios, the student made connections and conclusions about ideal deflector cone geometry trends. This research process also involved *Python* [2] programming to generate related graphs using pressure and temperature data from previous fluid-dynamic simulations. Relevant artistic renditions were created with artistic and graphic software to illustrate core concepts in the rocket-deflector scenario including the temperature gradient and molecular resultant properties of the plume near the deflector cone.

Beyond its technical contributions, this research process has been shown to provide significant educational benefits to the student researcher. Through the literature review process, the student developed a more efficient method for identifying relevant papers from reliable journals. This approach combined strategies learned in class, guidance from advisors, and practical insights from real-world trial and error. Then by analyzing equations, data, and experimental results from relevant papers to incorporate them into the research study, the student learned about fluid dynamics involving shock waves, boundary layers, and the effectiveness of dimples being the first exposure to such concepts. The student gained valuable experience analyzing raw simulation data, including temperature, pressure, and radial distance, and transforming it into meaningful graphs using *Python* [2]. This process required applying and expanding their programming skills, including refreshing previous classroom knowledge and learning new methods by self-learning with online resources, to effectively communicate complex trends visually on linear and logarithmic scales. The making of the artistic rendition proved to be a crucial part of the learning process as the student creatively found outlets using graphic

programs, something they were already comfortable with, to effectively communicate the rocket-deflector scenario visually.

The paper continues with a methodology section, which in greater detail outlines the methods of the student research involvement work. This is followed by a results and discussion section which delves into the research project and its findings. Finally, before the conclusion, there is an educational impact section that specifically connects methods to learning outcomes and determines educational effectiveness.

Methodology

The literature review approach primarily involved analyzing existing literature, equations, and experimental data to determine ideal deflector cone design characteristics involving its geometry and aerodynamic features. The student began searching for relevant and reliable literature by utilizing Google Scholar, Microsoft Copilot, and the institution's academic databases. After obtaining articles, the student identified and analyzed trends and relationships between key geometric variables, such as impingement angle, impingement distance, exit radius, and other critical design parameters. These variables were assessed for their relevance and applicability to the current research on deflector cone design, understanding that the scenarios presented in the literature differed in several key aspects from the specific context of this study. By dissecting mathematical models and data from the literature, the student established connections, leading the student toward conclusions about the most effective design considerations for deflector cones in a lunar environment. The reviewed studies primarily focused on rocket landing and launch dynamics, impinging jet behavior, and the performance characteristics of wedge and conic deflectors, providing a comprehensive foundation for the research at hand.

The student created graphical plots using *Python* [2] to visualize simulation data provided by other summer research students. This approach gave the student flexible control over the visuals, including framing, labeling, and scaling of the figures. The student was given ten sets of data total to make graphs from. Four sets had temperature values in Kelvin with corresponding values of radial distance from the center of the deflector in meters, which were plotted in Figure 1. Then the other four sets measured pressure values in Pascals instead of temperature, which were plotted in Figure 2. Each set of four tested four deflector shapes: parabolic, sinusoidal, conic, and a flat surface (naked landing pad with no deflector). The final two sets of data tested the flat

surface shape for its values of fluid viscosity, graphed as Figure 3, and density, graphed as Figure 4, with corresponding values of radial distance for each.

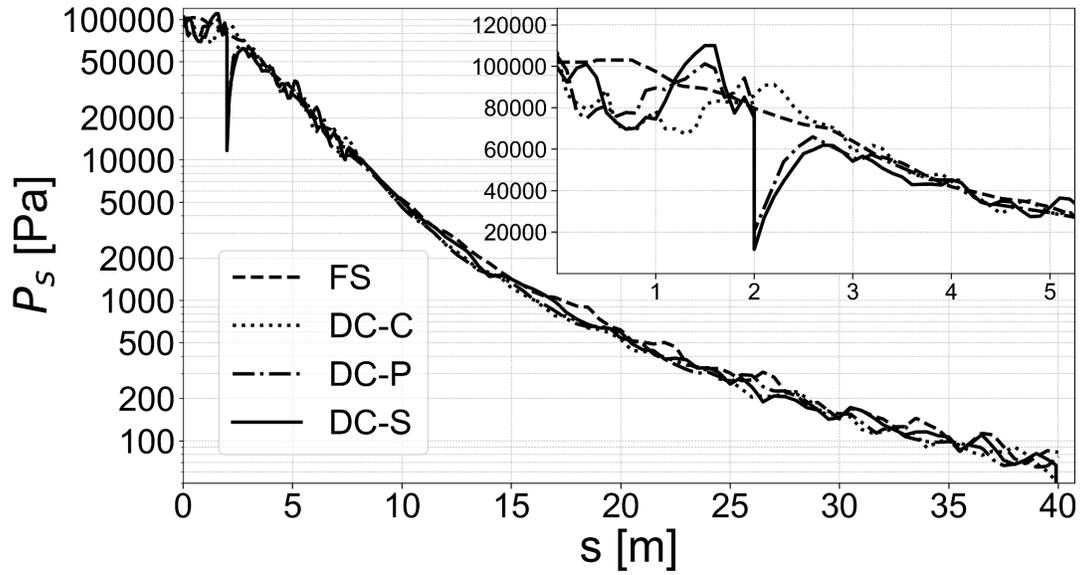


Figure 1. Deflector cone shapes graphed surface pressure over arc length

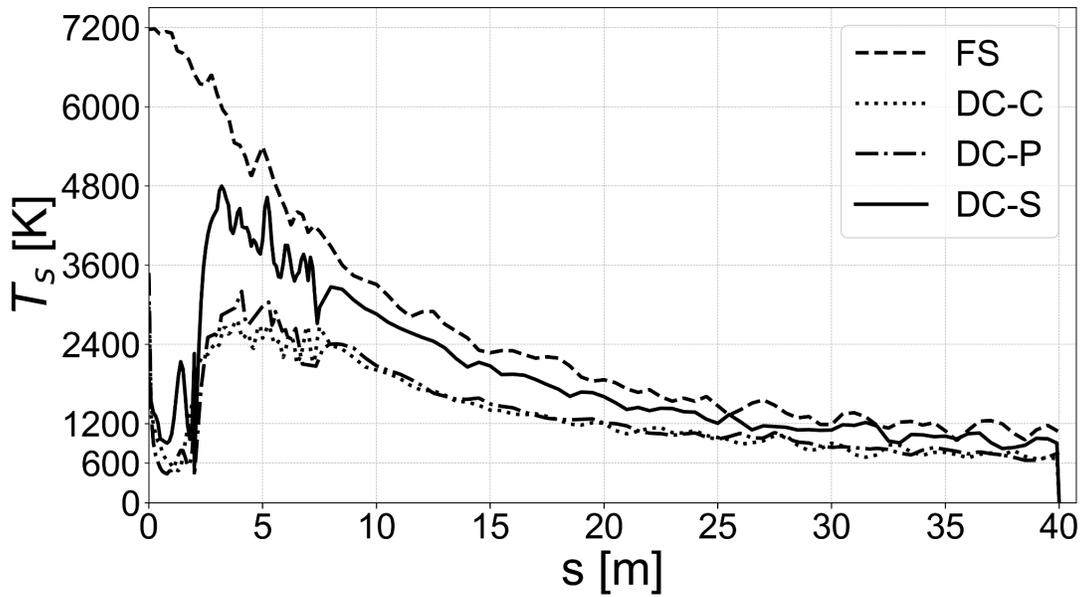


Figure 2. Deflector cone shapes graphed surface temperature over arc length

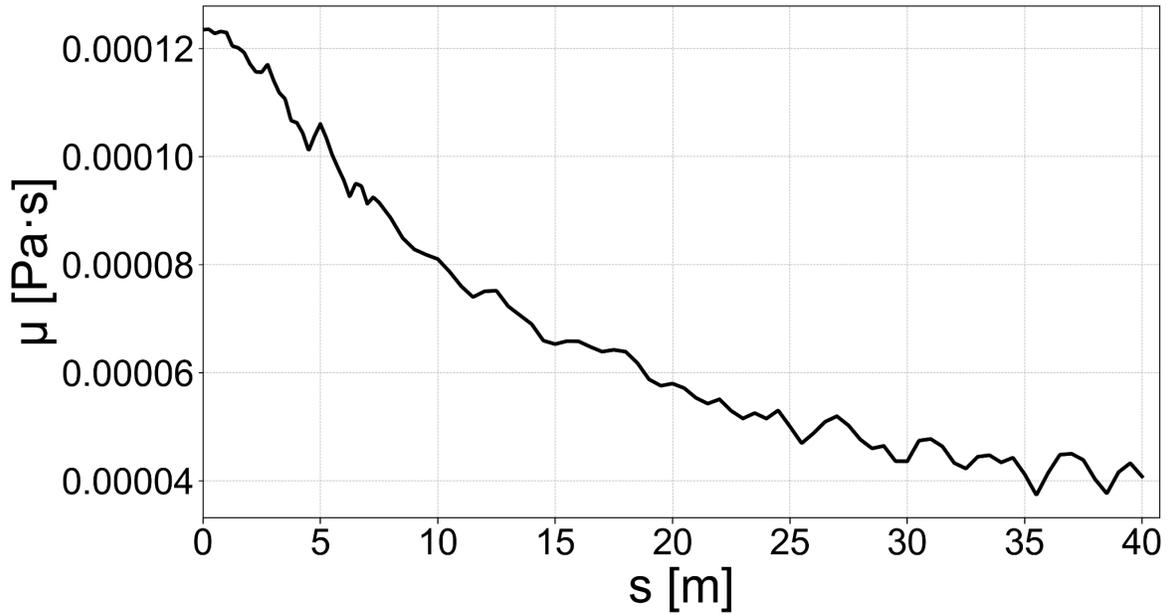


Figure 3. Flat surface graphed fluid viscosity over arc length

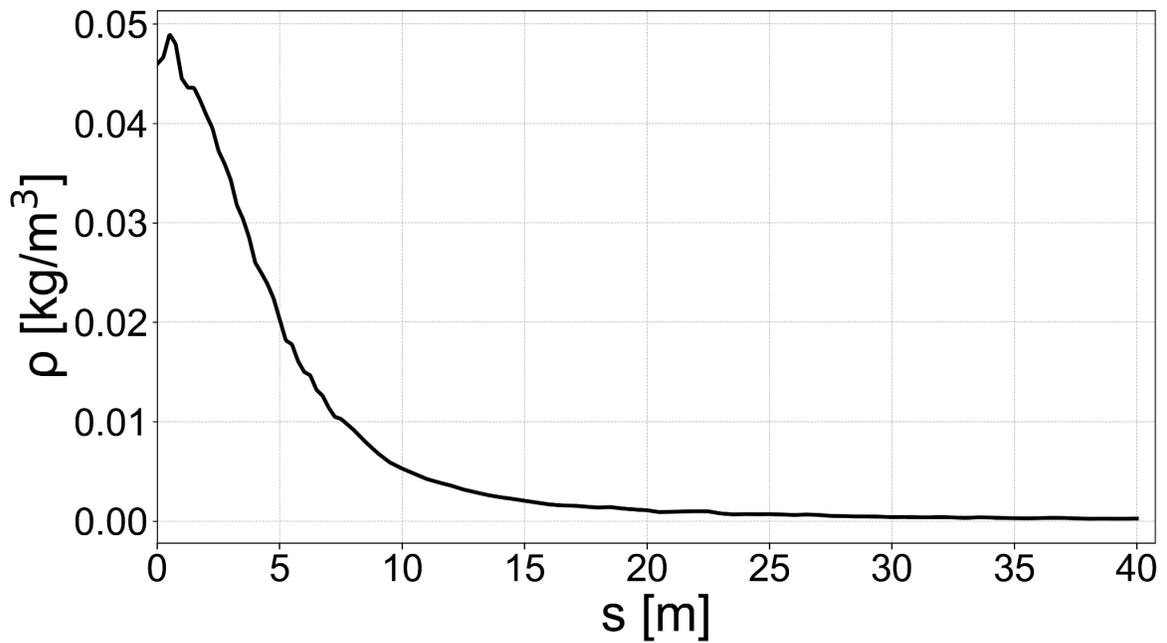


Figure 4. Flat surface graphed density over arc length

The student used both Computer-Aided Design (CAD) software *Solidworks* [3] and vector graphic software *Adobe Illustrator* [4] to create the artistic rendition. The student began by

creating a simplified model of the rocket-deflector scenario in *Solidworks*, using the SpaceX Starship as the rocket reference and selecting a reasonable size for the deflector cone. This was used to accurately communicate the scaling of the elements of the scenario as the student continued by taking a screenshot in a desired orientation. The student then opened this screenshot with *Adobe Illustrator*, which the student used as a guide when illustrating the rocket and deflector. The temperature gradient was designed after simulation graphic results were given to the student by another student researcher. The student illustrated the molecular dynamics based on simulation results provided by another student researcher, describing the proportions of molecules in the rocket's plume. The resulting graphic (Figure 1) accurately represents the plume's molecular composition.

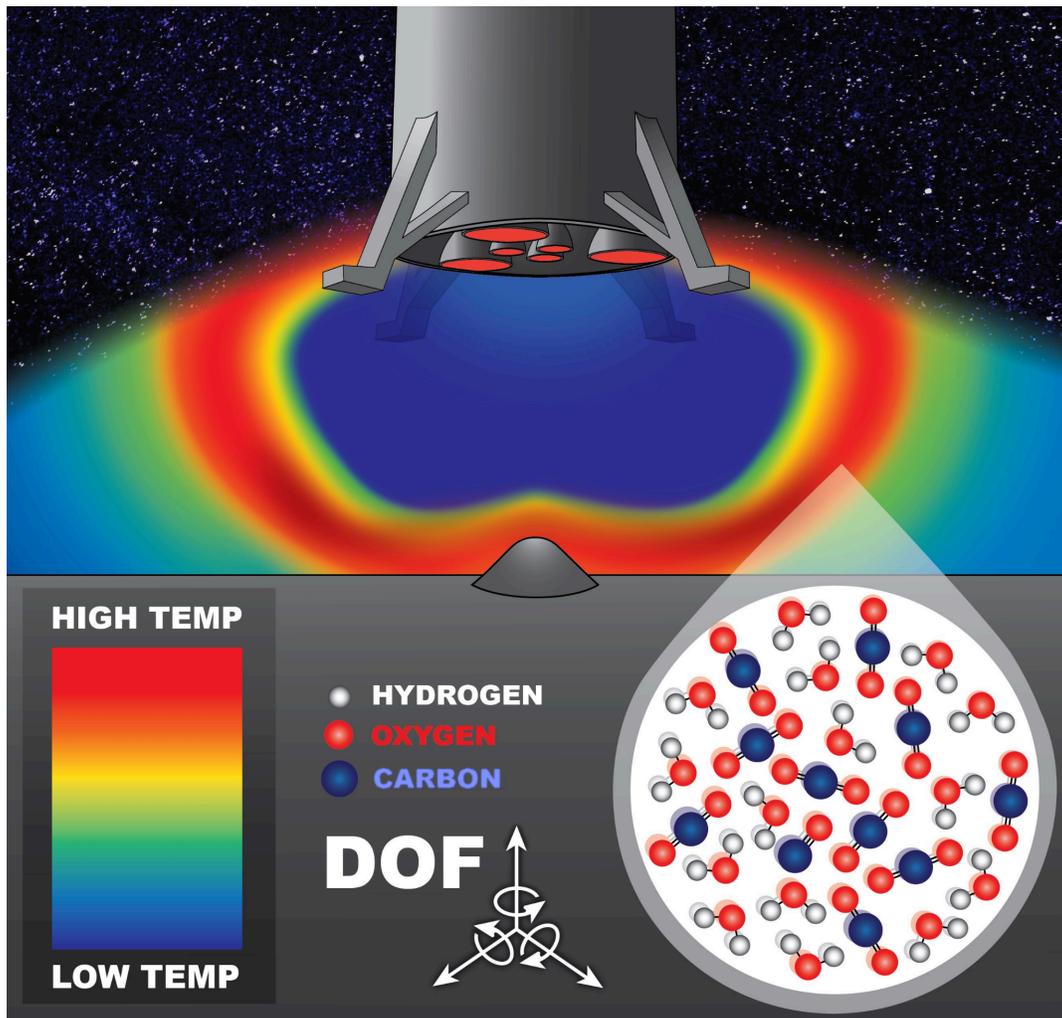


Figure 5. Rocket plume deflection, molecular dynamics, and temperature fluctuations.

Results & Discussions

One key article found was *Flame Deflector Design* [5] which described the minimum design requirements that NASA enforces for new flame deflectors. It included parameters such as impingement angle limits, impingement distance, exit radius, and thrust-to-weight ratios. It also outlined mathematical equations including surface pressure and temperature in relation to geometric values, the key variables the design aims to minimize. The paper defines the impingement angle as the angle that the deflector surface makes with the center axis of the nozzle at an instantaneous point. The NASA report suggests that the impingement angle generally should be no larger than 30 degrees. The impingement point should fall under half of a nozzle exit diameter upstream from the tangent point between curved and flat surfaces.

Through exploring the math outlined in *Flame Deflector Design* [5], the student suggested that the impingement angle and impingement point distance regulations may be attributed to a key equation outlined in the literature relating pressure to both impingement angle and impingement area

$$P_{ave} = \frac{F_N}{A} = \frac{T \sin(\delta)}{A} \quad (1)$$

In this equation, P_{ave} represents the average pressure in the primary impingement area, F_N which is the net normal force component, T is the sea level thrust force of the rocket engine, A is the primary impingement area, and δ the impingement angle. From this, we see, that as the impingement angle for this deflector increases, the pressure increases, and as the impingement angle decreases, the pressure decreases. Looking at this equation alone, deflector designers should aim to minimize the impingement angle, which is why this article encourages a maximum impingement angle for this design, and to maximize the impingement area, which is why this article encourages a minimum impingement point distance (which is related to the area) value for this design. However, there may be other factors to consider regarding these design variables.

The heat on the deflector's surface is also related to the exit radius and impingement angle variables through equations outlined by *Flame Deflector Design*.

$$q = q_r + q_c + q_p \quad (2)$$

$$q_r = 0.2q \quad (3)$$

$$q_c = \frac{q_{stag}}{S_c \sqrt{R_{eff}}} f(\delta) \quad (4)$$

$$q_p = a_c \sin(\delta) (TE - h_w) \quad (5)$$

In Eq. 2, q is the net heat transfer rate, q_r is the radiant heat transfer rate, q_c is the convective heat transfer rate, and q_p is the particle heat transfer rate. Eq. 2 introduces q_{stag} which is the stagnation point heat transfer rate, S_c which is the shape coefficient, R_{eff} is the effective radius of curvature of the deflector, and $f(\delta)$ is the local stagnation point heating ratio for a certain δ . R_{eff} is likely related to the shape and size of the deflector, possibly including the impingement angle and the exit radius. Maximizing R_{eff} is a design aim in the process of minimizing the heat on the deflector. Unfortunately, the exact relationships between R_{eff} and these geometric variables are unspecified in *Flate Deflector Design* [1]. Eq. 4 does relate δ , which shows that once again minimizing the impingement angle is desirable in reducing the heat. Even though this NASA report refers specifically to wedge deflectors, these outlined trends and concepts can be translated to deflector cones.

Another article was *A review of impinging jets during rocket launching* [6] by Jiang et al which reviewed multiple studies regarding impinging jets during rocket launching. One of the many papers discussed in the paper reviewed was by Hunt and Lamond [7], which experimented with different apex wedge angles (90-degree, 60-degree, and 45-degree) and surface pressure measurements. The trend between these three angles was that as the wedge angle decreased, the surface pressure decreased. In contrast, the impingement distance was nearly independent of the surface pressure in these tests. Another article reviewed is by Patel and Matthew [8]. This paper describes how the impinging jet is steady at an impingement distance of 1 nozzle diameter but once it reaches about 4 times the nozzle diameter, large oscillations occur in the flowfield and the overall sound pressure level (OASPL) increases by 7 dB. However, a larger wedge angle produces a detached shock, resulting in an OASPL that is 3 dB higher than the OASPL of an attached shock, which occurs with a smaller wedge angle. This again reinforces the benefit of the minimizing impingement angle design goal.

Experimental and Numerical Research on the Diversion Effect of a Conic Flame Deflector for a Lunar Module Ascent Stage [6] tests the pressure exerted back onto a descent model at different points from the deflection of a conic deflector with changing variables like impingement distance and impingement angle. One interesting main finding relevant to this report is that this conic deflector initiates a correcting torque on the model as it is inclined. This torque increases with a decreasing impingement distance and an increasing impingement angle. However, this finding doesn't fit in with the scope of our project since inclined rockets are not what this study is concerned with. Overall this study looks at how the deflected exhaust puts pressure back on the descent model, which significantly increases as the impingement distance decreases. The overall effectiveness of how a conic deflector diverges exhaust also shines when the study compares pressure results between the cone shape and a flat plate. It shows how much slower the pressure falls as impingement distance decreases for a flat plate versus a conic deflector. This demonstrates how this study reestablishes this project's central idea: that conic deflectors effectively diverge exhaust.

The student explored the concept of implementing dimples in a deflector design considering that it could potentially enhance its aerodynamic properties. It was concluded that it would only likely be effective on surfaces closer to the rocket's nozzle. It would only be at these locations where the rocket's exhaust flow Reynold's number significantly contributes to the flow character. This is because of the great pressure of the exhaust gas, which could effectively fill in the volume of space nearby where it is being shot out. The exhaust gas would then dissipate into the surrounding ambiance increasingly more as the distance from the nozzle increases, making the dominant plume fluid closer to the lunar environment in regions further from the nozzle. The student suggested that experiments in this area should be conducted to find more specific details on where the flow characteristics transition locations are and to confirm this hypothesis.

The literature review provided a comprehensive foundation for giving insight into how to effectively design a deflector cone that minimizes surface pressure, temperature, and acoustic loads ensuring safety and efficiency in lunar landing scenarios. The student determined that minimizing the impingement angle is an effective deflector design goal as it reduces the surface pressure and temperature, which would otherwise lead to swifter erosion. The student also discovered allusions that a smaller angle leads to a smaller acoustic load. Ultimately, the results of this literature review underscored the need for intentional and calculated decisions over geometric parameters in deflector cones to achieve a durable and safe deflector cone optimized for lunar landings.

Educational Impact

This research project about deflector cones proved to be a very significant point in the student's engineering education. It served as the bridge between theoretical classroom concepts and practical real-world applications and significance, leading to self-directed learning and skill development crucial for a professional career in engineering and design. Every stage of the project presented unique challenges and approaches that turned into opportunities for learning and personal growth.

The literature review process was one of these transformative processes, requiring the student to efficiently locate, select, analyze, and synthesize information about deflectors from reliable sources. This included developing strategies to find the most relevant studies using tools like Google Scholar and the student's institution's academic databases. Often using these tools required advanced searches, which the student learned how to take advantage of. The student also occasionally used Microsoft's AI browser, Copilot, as it managed to search and cite articles answering specific questions about different deflector design variables, implementing dimples on a lunar environment, or related concepts. In the process of locating reliable articles, the student learned to scrutinize journal articles by examining the authors, and associated organizations, and checking to see if they have been peer-reviewed. As an initial check for relevance to lunar deflector cones, the student reviewed the abstracts and introductions of the found papers. These developed methods proved useful for acquiring information about the ideal deflector cone designs. They also formed and developed article-sourcing skills that are important for the student's development both as a scholar and as a future professional engineer.

In the actual review of the found papers, the student learned to read through the entire paper while annotating, a process of asking questions, answering questions, and highlighting key findings as a way to engage and to keep up with the literature, also allowing a way to connect questions and insights between different articles. This was done for all the reviewed papers, often focussing on annotating and noting details about design variables and their relationships to surface temperature, pressure, and acoustic effects. The next focus would go into examining the graphs, figures, data, and equations and rereading the paper's corresponding analysis. The student would then determine which design variables were the most influential according to the results, generally relating to surface pressure, temperature, and acoustic loads. Rarely were these design variables explicitly stated in the literature, which required the student to analyze and

connect overlapping concepts from different articles and engineering educational resources to determinations. By doing this, the student not only deepened their understanding of fluid dynamics, impinging jet behavior, and the effects of geometric variables like impingement angle and distance on pressure and temperature but also their overall general confidence and ability to read, understand, and apply complicated scientific articles. As discussed, this literature review experience cultivated skills in critical thinking, analytical reasoning, and an enhanced ability to interpret inexplicit data, which are foundational for engineering problem-solving and learning.

Programming and data visualization were another cornerstone of the educational impact. With the challenge of having to make customizable plots presented, the student was led to relearn basic *Python* [2] programming knowledge and learn new programming techniques to have the ability to fine-tune control of the graph's visuals, framing, labeling, and scaling. In addition to relearning the syntax, the student learned how to import modules into *Python* and to import data from CSV files. Both online tutorials and AI resources assisted this self-directed learning process. The student continued to expand their *Python* knowledge by learning to scale axes logarithmically and to place smaller zoomed-in inset plots. The ability to effectively visualize trends using tools like linear and logarithmic scales provided insight into the physical phenomena regarding pressure, temperature, viscosity, and density, better equipping the student's knowledge of the research at hand. Moreover, the tedious process of debugging fostered resilience, attention to visual detail, and a confident commitment to producing high-quality work.

The artistic rendition illustrating the process demonstrated the value of creativity in engineering and education. Using *Solidworks* [3] and *Adobe Illustrator* [4], the student applied technical knowledge of both of the contrasting software, to create a scale-accurate visual representation of the rocket-deflector scenario that is aesthetically appealing and effective in communication. This process combined elements of CAD modeling, graphic design, and scientific communication, illustrating the importance of interdisciplinary skills in conveying complex engineering concepts. This opportunity also allowed the student to build on existing graphic design expertise, demonstrating that engineering can integrate creativity and innovation alongside its traditional technicality.

Finally, the collaborative aspects of the research were also an important part of the student's learning and development of key engineering skills of teamwork and communication. By working under the guidance of a professor and alongside other student researchers exposed the student to constructive feedback and confirming encouragement. The student was required to interpret requests communicated by another student researcher who desired to transform data

into plots. Another key instance of communication was when a student researcher, who specialized in molecular chemistry, had to communicate his findings about the molecular dynamics of the rocket plume. In both these cases, the student had to engage with his teammates by asking questions and making his requests. The student's own presentation of findings and experiences to professors and peers strengthened their ability to communicate technical ideas effectively, which is a vital skill for personal growth and collaboration in any discipline.

This research experience has been shown to be beneficial in many ways to the student's engineering education and future career. By recognizing the responsibility and privilege of contributing to the real-world research subject, the student attributed this research process's success in this way to how it fostered an authentic desire to effectively contribute, and in that, learning much along the way about the subject and through the methods utilized. Translating this student's experience to the larger engineering classroom dynamic would suggest that students would benefit from having more project-based learning opportunities. Ideally, these projects would hold a greater significance to the student than theoretical scenarios that stay exclusively inside the classroom. Like the engineering student in this study, the desire to learn could come out of a genuine interest in the project's subject and its outcome. Practically, professors could encourage students to choose class projects aligned with their interests. Another impactful approach is for professors to look for ways to extend projects beyond the classroom. One way is to integrate them with opportunities to present at conferences or larger school events, similar to the outcomes of this very paper. Beyond the privilege and responsibility of presenting, such experiences would serve as valuable additions to students' resumes, further incentivizing their participation and effort. Incorporating real-world applications and fostering an authentic sense of responsibility and interest in class projects may greatly benefit the college-level engineering classroom, creating more meaningful and lasting learning experiences, and better preparation for students' future careers.

Conclusion

This research project on the geometrical characteristics of deflector cones for lunar landing pads highlights the learning potential of undergraduate engineering research. The study combined theoretical classroom knowledge and practical applications, enabling the student researcher to explore the overlaps of fluid dynamics and engineering design in addressing the challenges presented in the current moon landing process. Through an extensive process of literature review, programming, data visualization, and creative artistic applications, the research learning

outcomes have also demonstrated the importance of interdisciplinary approaches to solving and communicating complex engineering concepts. Through this exclusive engagement in contributing to real-world space exploration solutions, the student has reported a sense of fulfillment, excitement, and commitment to engineering. This experience led the student to consider pursuing aerospace engineering where involvement similar to this could continue. Moreover, this student's research experience translates to illustrate the broader educational value of project-based learning in engineering classrooms. By integrating real-world applications and fostering a sense of authentic responsibility and interest, these opportunities enhance engagement by allowing projects' significance to extend beyond the classroom. Ultimately, this work reinforces the value of experiential learning in engineering education, exhibiting how real-world research opportunities can inspire creativity, resilience, and a commitment to meaningful contributions in STEM fields.

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