

Investigating the use of thrust nozzles in extra-territorial rover applications.

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Abstract. Rovers exploring extraterrestrial terrains, such as Mars, face significant challenges in traversing loose soil and sand traps, often resulting in immobilization and mission failure. This study proposes a novel emergency system utilizing compressed air thrust to assist rovers in regaining traction and escaping compromised situations, the study aims to find the most thrust effective way to help the rovers regain traction. The system consists of hermetically sealed air containers connected to optimized nozzles, capable of delivering controlled bursts of thrust. Computational Fluid Dynamics (CFD) simulations using ANSYS Fluent were conducted to analyze various nozzle geometries, including dual bell designs, for thrust output, flow rate, and air efficiency. Results indicate that a dual bell nozzle provides the highest thrust (906.7 N) while balancing air consumption, enabling effective recovery with minimal resource expenditure. By providing at least 65% of the rover's weight as additional force, the system ensures traction recovery without complete air depletion. This approach enhances rover survivability, enabling exploration of challenging terrains and reducing mission risks. The study tests a number of nozzles to find the nozzle that exerts the maximum amount of thrust with a set volume of compressed air, the selected nozzle with the best results is an iteration of the bell nozzle with an adapted shape generating 820.16N with the pressure supplied.

Keywords: CFD, Thrust Nozzle, Mars Rover

1 Introduction

Three of the six rovers that have ever successfully robotically operated on the Martian surface have faced considerable difficulties in traversing the Martian terrain. Engineers and technicians spend a lot of time trying to fix such situations by simulating situations on Earth and commanding the rover to carefully maneuver out but with a low chance of success. One of the examples would be Spirit, one of the rovers, which became permanently stuck in a patch of loose soil after its wheels lost traction. Opportunity, another Mars rover, became immobilized in a soft dune taking engineers over a month of careful maneuvering to free the rover. Curiosity, in 2014, had to reroute after encountering soft,

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loose soil in "Hidden Valley," which posed a risk of immobilization[1]. One can say that rovers are essential components for the exploration of extraterrestrial bodies. Besides the effort of loads of people that goes into building them, they cost millions of dollars to develop and launch. Hence, losing these rovers leads to a heavy loss of funds and manpower. The Mars Exploration Rovers (MERs), i.e. Spirit and Opportunity, involved a launch and development cost of over \$700 million[2]. They were a joint effort by humanity to explore Mars, taking over 3 years to develop. A tumble into the Martian sand is all it takes to lose all that effort!

A newer rover, Perseverance, uses stronger wheels, and an enhanced Autonomous Navigation System (AutoNav)[3] that uses high-resolution cameras, including Mastcam-Z and Navcams[4], to identify potentially hazardous terrain (like loose soil or steep slopes) and plot safer routes in real-time with the help of a team on Earth. It also uses a rocker-bogie suspension system[5] (similar to Curiosity's) that allows it to climb over obstacles up to 19 inches tall while keeping all six wheels on the ground for stability. While the Chinese Zhurong Rover (Tianwen-1) employs a combination of articulated suspension[6] and independent 6-wheel actuation for enhanced adaptability.

This study aims to provide a way for rovers to provide themselves an instant boost or thrust by delivering compressed air stored in a hermetically sealed container through two nozzles fitted on the rover. The air expelled through the nozzles will be able to provide torque and thrust to aid the rover in maneuvering out of its compromised state. Determining the nozzle geometries to use for optimum thrust and duration of expelling air was one of the challenges. Utilizing the Fluent module in Ansys, data was gathered, regarding the thrust generated, flow rate, pressure gradient/contour, and velocity gradient/contour, for various nozzles, each of different types and geometry. The container needs to be hermetically sealed to ensure no leakage and waste of payload on reaching extraterrestrial bodies. Hence, this system will act as a one-time emergency system. It has various applications such as aiding the rover to escape a Martian sand trap, providing them a boost to get out of sticky situations, etc.

These applications provide a way for the rover to escape emergency situations. Engineering solutions such as the above-mentioned compressed air system may increase the probability of rovers surviving on extraterrestrial bodies where direct human intervention is not possible. This will allow humanity to explore those parts of the extraterrestrial bodies that require taking trickier paths to reach as humanity is forever seeking discovery. This research study suggests an innovative insight into the traction regain ability of the rover using a nozzle to release the weight of the rover from the stuck wheels and later regain the traction on a more stable patch of land to ensure the rover can continue operation.

1.1 Literature review

R. Kujala et al. [7] focused on presenting the definition of Maximum Design Pressure (MDP) and the procedure used to derive it, which is needed for adequate design based on applying safety factors to MDP. It also gives definitions to the Pressurized hardware and its sub-divisions namely Pressurized Vessels, Pressurized Structures, Lines, Fittings, etc. MDP is determined using five primary steps: Thermal Environments, Credible Mechanical & Electric Failures, Procedural Errors, and External Pressure Reduction. The design approach to avoid rupture is DFMR, while it is DFMR and fault tolerance for Rupture. It provides safety factors that are used to calculate the needed structural strength of the material.

However, it does not provide a formula for the direct calculation of MDH. MDP is computed about a two-fault tolerance concept (2FT).

It is the intention of Fanrui Cheng et al. [8] to study the flow in a simplified laval nozzle which has many usages in the aerospace industry, especially in the rocket engines. The researchers investigate the effectiveness of gas behavior simulators using two numerical methods, Euler, and small disturbance equations. The emphasis is put on the results of the methods and on pointing out the similarities and differences in the results. Differences in the behavior of shock waves are noticeable as well. One significant difference is that the Euler equations were only computed for a single horizontal centerline of the nozzle which is a possible limitation for complex behaviors in 2D. On the other hand, Jeffrey Antol et al.[9] detail the prototype design and instrumentation to be fitted, the preliminary test results, as well as the Mars Tumbleweed Rover's future development and testing plans. The rovers are simple and cheap, and they operate using the Martian winds to traverse its surface; hence, they can conduct random surveys, locate places of interest, and scout human landing sites. Moreover, NASA Langley Research Center LaRC has come up with several concepts very novel in nature such as deployable open-structure Tumbleweeds, including the Box Kite, Dandelion, Eggbeater Dandelion, and Tumble-Cup. These can also be used to explore places where conventional rovers cannot reach. A prototype was made with 3-foot long pieces of 1/8 inch diameter titanium wire 6Al 4 V ELI connected with polycarbonate to make hoops, which formed. The sails are made of 1.5 oz/yd rip-stop nylon sail cloth, and the sails are secured to specially shaped orthogonal hoops with Velcro. Thermocouples, pressure sensors, and the GPS Antenna were also mounted to the sails and fastened with Velcro.

Andrew J. Coates et al.[10] highlights the importance of the ExoMars PanCam instrument and the other tools associated with it in what the mission entails while going to Mars. PanCam integrates morphology, geology, and atmosphere of Mars which are all critical data for determining the biosignature and its existence in the history of Mars. It comprises two Wide Angle Cameras (WACs) and one High-Resolution Camera (HRC) to image rocks in detail at different angles. It gathers information needed on the topography of the Martian surface to model a 3D map. The instrument needs to be adjusted to increase the accuracy of the data collected. PanCam synergistically cooperates at an operational level with an Infrared Spectrometer (ISEM) and Ground Penetrating Radar (WISDOM), so that more complete data are collected for the analysis and information needed to create the three-dimensional map of the Martian surface. One of the beautiful parts of the work that remains to be completed is the survey of Mars' atmosphere, determination of drilling location, and comprehension of the geology of Mars and its life-supporting conditions. One oversight in their implementation is that PanCam has not been designed to avoid the Martian sand that could blur the images by sticking to the lenses. Also, they failed to take into account that while building a 3D model of Mars to know where to go or not, how would they exit the perilous zone after capturing some of the data.

P. Poulakis et al.[11] Addressing the need for a simulation environment that can model various developments of planetary rovers is a daunting task because it is difficult to replicate the conditions on Earth while target environments remain highly dynamic. sub-systems of a rover and the planetary environment to support end-to-end mission simulations due to these challenges in designing and testing planetary rovers. The 3DROV system uses the SIMSAT simulation framework, which represents the heart of data management and running simulations. The representation of sub-systems can be done across different physical domains. The sub-systems can be altered based on a necessity. The paper makes an overview of the newly undertaken work for the integration of single components, the system planning methods, and six strain gauges for checking the system validation. The progress outlined in the figures indicates that the 3DROV system is at an incomplete stage

of development; however, it has some progress, but no specific quantitative results are listed. Among the key milestones attained so far, is the integration of sub-systems and the establishment of robust simulation environments. More validation methods are needed, which highlights the point that comprehensive testing and validation of the models and the subsystems have yet to be done, while the right side of the diagram is still under construction.

Geoffrey A. Landis et al.[12] explain the challenge of surveying the surface of Venus, which has an extreme condition such as an average temperature of The size of the sails that were incorporated, the specifications of the wheels as well as the power requirement were all analyzed. The research work culminates in the conclusion that the design for a sail-propelled rover is realistic. It has the capability of landing a mass of 265 kg with a total sail area of 12 m. The mission objective is to go to the planet for 50 days' worth of data collection over geology and atmospheric conditions. An analysis was presented where the rover was capable of going at 4 cm/s in the proper wind conditions, the rover should be able to return considerable scientific data from its mission. With all the promise of the design, there are still considerable gaps. High-temperature electronics are still in the process of being developed and extensive testing still needs to be done to make sure that the technology will be reliable in the harsh environment of Venus. The study has little to say about the problems of navigation and how to address them. The wind propulsion mechanism that the rover relies on would prevent movement during low wind speed times. The initial primary goal of the Mars Science Laboratory mission with the Curiosity rover, as Vasavada et al. [13] deplore, is to understand whether Mars is a planet that can support life. In doing this, there is a need to provide an analysis of the geologic and environmental history of Gale Crater mostly on the conditions which may have existed in the past that could have supported life. Curiosity has done geochemical and miner sediment transport and helped understand the evolution of Bedford, while one of its aspects was the monitoring of the Martian atmosphere for radiation and Methane. Gale's mission provided very strong evidence that Gale's craters have collected river sediment for lake formational purposes, which by itself indicates that environmental conditions were life-friendly 36 years ago.

Khade et al [14] bring up the problem of the relatively slow operating speed of the rovers, which retards their effectiveness in the exploration of other celestial bodies like Mars and the Moon. Due to extreme environmental conditions and communication roadblocks, the rovers need to travel at greater speeds. The document describes a novel suspension type that will prevent rollover while maintaining a high speed. Kinematic analysis was also done to compare the operation of the newly proposed suspension type with the existing ones. The study assists in determining how the new configuration can successfully negotiate different terrain features and remain stable. The new system is also fitted with environment sensors to monitor the atmospheric conditions. Such devices enable rovers to navigate across the terrain at greater speeds while still achieving stability and data acquisition with their environmental sensors. Discussion surrounding the durability of the new system in the extreme environment has however been minimal. overcome challenges. The rocker-bogie suspension system, which comes from traditional systems, can lose grip due to uneven weight distribution to the wheels and as a result, the rover would not be able to climb the obstacles. This study focuses on evaluating modified rockers that possess a preloaded or wound spring and enhance load distribution and traction when moving toward the obstacle. In a certain paper by Cosenza et al.[15] a set of different conditions was developed to widen the scope of analysis for modified bogie suspension systems. It incorporates the adjustable torsion spring to optimize the wheel load at both static and dynamic sim. The study involved a blend of theoretical and numerical simulations with varying conditions which

included friction coefficient values and spring preload values [16,17]. The outcomes demonstrated that the over-mounted torsion spring positively influenced the rover's ability to traverse innumerable obstacles. This is also in conjunction with simulation-derived results which indicate improvement. However, it suffices to say that although progress has been made, the paper suggests practical testing is required to back up the proposed changes. For their paper, authors Laksh Raura et al. [18] addressed the main issue related to the existing rovers by carrying on the expensive instrumental payload for Mars Exploration Rovers and Mars Science Laboratory MSL which has resulted in the rovers being very costly and heavy to build. However, there is a need for low-cost compact rovers that are capable of accomplishing the target needs. They also focused on the extreme environmental conditions of the rover, which primarily contributed to communication loss. The last communication received from the rover suggested that it was nonoperational due to dust covering the solar panels and other extreme environmental conditions that were not expected. The mission provided lessons on the design and operational issues for future Mars missions, with emphasis on improved thermal management and dust control for rovers.

Shivakumar S. et al. [19] work towards solving the problem of urban air emissions with friendly means of transport due to its ever-growing need. It emphasizes the competitive advantage of compressed air vehicles, which is the absence of pollution. The research involves an analysis of the existing literature on compressed air vehicles [20]. It also considers the adaptation of the gasoline engine into compressed air engines, as well as the development of new technologies such as multi-fuel engines which work with compressed air and gasoline. The research goes on to reveal that indeed CAVs will be cheaper than electric or hydrogen cars. As stated in the paper, with over 10 years of research and development efforts devoted to CAVs they will be performant enough for today's standards. These advancements tend to limit progress when it comes to learning how to manipulate compressed air parameters like temperature and energy density for safety and expense purposes. Goldberg et al. [21] tried to resolve the conflict of safely guiding rovers through uncharted and dangerous areas of Mars. Contemporary radiation-hardened processors have a computational sufficiency limit, and that range is the goal that science can reach within the absolute time frame allotted to the rovers. Through building a local map of the terrain, the authors implemented stereo vision with geometric analysis and created a computerized autonomous navigation system. The importance of combinatorial optimization provides statistics of the surface moment to draw the overall hybrid mapping. The paper provides a baseline recording of speed increases in the stereo vision software which since has been updated to use vectorized instructions for the purpose of modern CPUs. Performance benchmarking is also discussed indicating that commercial-grade processors could provide substantial speedups over radiation-hardened ones. However, the complexity of the algorithms may need to increase to improve navigation performance in rough terrain, indicating that current implementations may not be fully optimized for all conditions.

This research aims to provide a system for rovers on extraterrestrial bodies to escape emergencies, such as immobilization due to sand, by analyzing the design of a compressed air system to provide torque and thrust, allowing the wheels to gain traction, and thus preventing disaster. This system would provide a life-saving grace to any rover on extraterrestrial bodies, allowing the mission to continue and saving the effort and money that went into the development of the rover.

2 Methodology

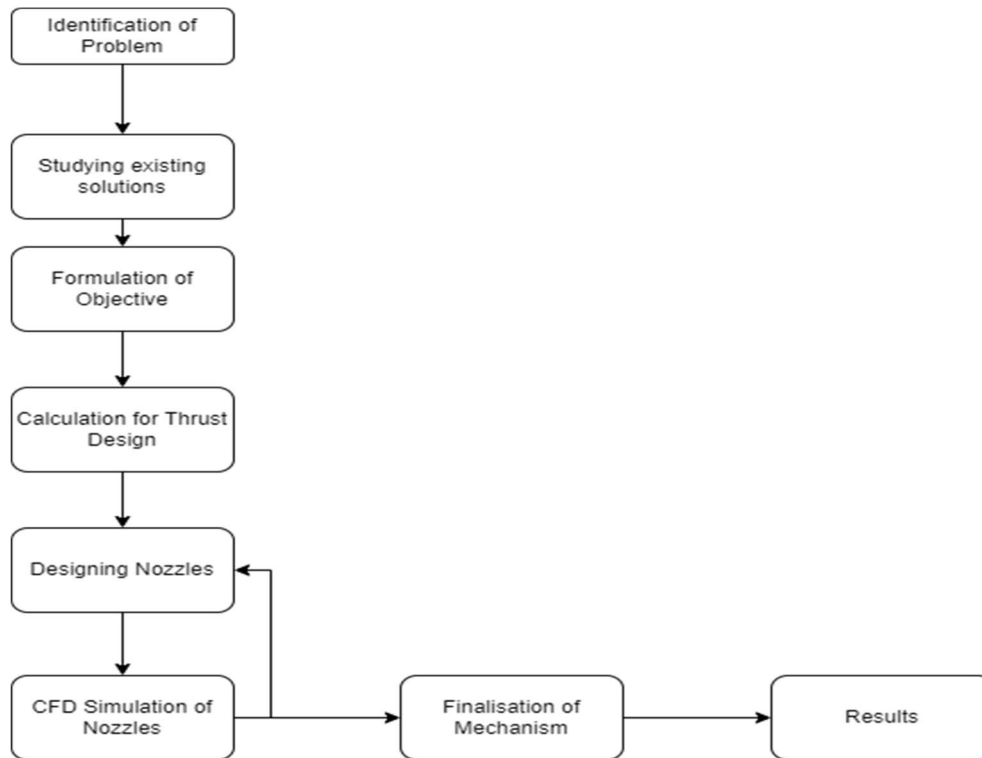


Fig. 1. A Flow Chart for Methodology

Figure 1 shows the systematic methodology followed for research. Initially using the literature reviews, the objective of the research is created, and further procedure is written below.

2.1 Theoretical thrust calculations

The rovers that get stuck need to be free to continue their mission. Providing thrust to the rover, in such positions, while rotating the wheels at full speed, should help the rover to get free. The thrust need not lift the rover into the air, it merely needs to help the rover by providing torque and force to practically push the rover out of the unfavorable terrain. A hermetically sealed container with internal pressure exceeding 500 psi should be connected to nozzles that provide high amounts of thrust while expelling minimal air.

Calculating Thrust: $F = ma$

Where,

F = Force required to lift the entire rover in N

m = Mass of the rover in kg

a = value of acceleration due to gravity at the rover's position in m/s^2

The acceleration due to gravity on Mars is $3.72076 m/s^2$

The acceleration due to gravity on Earth is $9.81 m/s^2$

Force required to lift = 200 Kg on earth force required to lift completely would be 1962 N
Whereas, on Mars, it would be 744.0152 N

Hence, for a 200 kg rover, we require ~745 N of thrust on Mars to lift the rover. In this case, it is not required to lift the rover completely off the ground. It just needs to provide ~65% of the rover's weight to allow the wheels to gain back traction, evacuate the area, and continue the mission, hence about 485 N needs to be produced.

Further based on the theoretical calculation, nozzles were iterated to evaluate which nozzles perform the best for the same, the total length of the nozzles was kept the same to ensure they can be accommodated within the rover's body and conversely keep the results consistent.

2.2 Design of the Nozzle

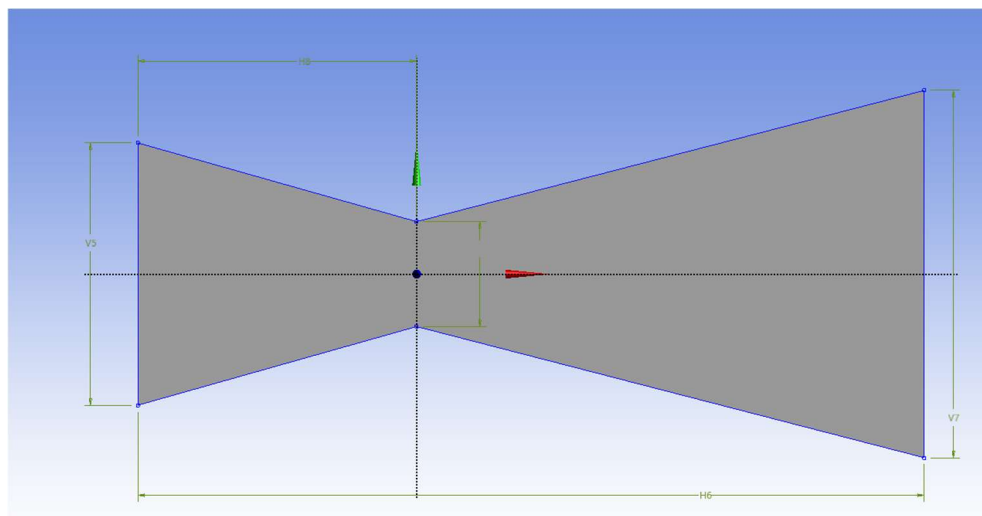


Fig. 2. CD Nozzle - 2D design

This study aims to assist the rover in recovering from a compromised position, thus nozzles are required which provide the most thrust while expelling the minimum amount of air so as to increase the duration of the thrust provided. A balance between the thrust provided and the rate of discharge of air needs to be maintained.

Various types of nozzle geometries – Convergent-Divergent, Bell, Dual Bell – were iterated using the Fluid flow fluent module within ANSYS, figure 2 shows the CD nozzle. Over 20 different nozzles with varying geometry, throat diameter, inlet diameter, outlet diameter, and general shape were used to perform a Computational Fluid Dynamics Analysis (CFD Analysis), Data including thrust produced, the velocity of air at the outlet, pressure gradient/contour, velocity gradient/contour, and the flow rate were calculated for each.

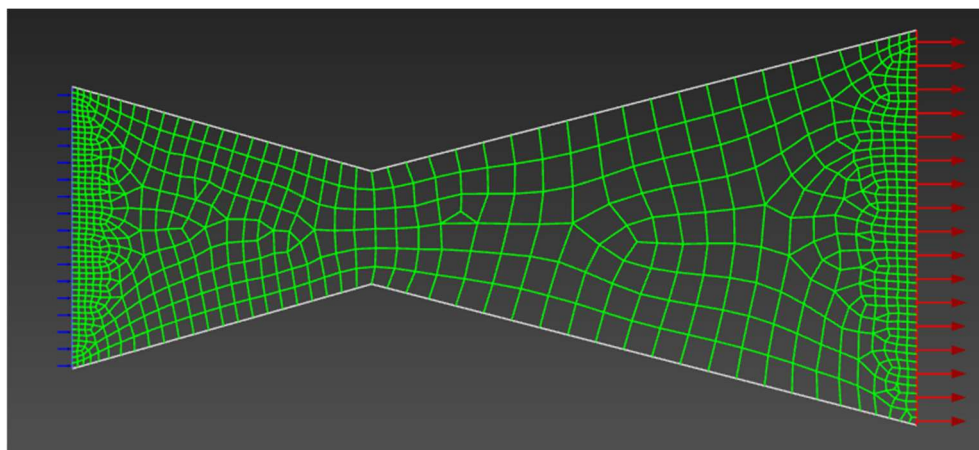


Fig. 3.: Meshing of Nozzle in the FLUENT module of ANSYS

Figure 3 represents the meshing strategy used for the CD nozzle to perform the CFD simulation and to find the thrust value. As this flow was internal airflow K-omega. Mesh is utilized to split the body into infinitesimally small parts so that a study can be carried out on each one of these “nodes” and subsequently analyzed per node. Once the Mesh has been updated in the solver section other constraints and boundary conditions are applied and the iteration step is set till the solution doesn’t converge. The results of the same are written in the next section of the research. The study was created on a surface plane (2D), next the body was meshed using the mechanical module within the ANSYS workbench, the boundary conditions were then set and the model was run with 1000 iterations to give it enough number of iterations till convergence is achieved.

3 Results & Discussion

Simulating the nozzle’s thrust output was an essential part of this research. Using the FLUENT module of Ansys, gradients/contours of pressure and velocity were generated for each nozzle.

Table 1 shows the values of force extracted from ansys post processing, at the outlet side.

Table 1. Force at nozzle outlet obtained by simulation through FLUENT module of Ansys.

S. No.	Type of Nozzle	Subtype	Inlet Diameter	Outlet Diameter	Total Length	Throat Diameter	Force Value
1	Conical	-	100	140	300	40	69.9618 [N]
2	Conical	-	100	140	300	10	9.78384 [N]
3	Bell	Conventional	100	150	300	40	410.589 [N]
4	Conical	-	100	140	300	60	111.442 [N]
5	Conical	-	100	140	300	70	121.595 [N]
6	Conical	-	100	140	300	40	65.9982 [N]

7	Conical	-	100	140	300	30	44.6476 [N]
8	Conical	-	100	110	300	40	58.8147 [N]
9	Conical	-	100	160	300	40	66.5438 [N]
10	Bell	Conventional	100	150	300	25	161.261 [N]
11	Bell	Conventional	100	180	300	40	535.399 [N]
12	Bell	Conventional	100	200	300	40	609.922 [N]
13	Bell	Conventional	70	200	300	40	627.514 [N]
14	Bell	Conventional	70	220	300	30	488.036 [N]
15	Bell	Conventional	70	200	300	30	475.519 [N]
16	Bell	Conventional	70	200	300	40	668.041 [N]
17	Bell	Conventional	70	200	300	40	602.668 [N]
18	Bell	Conventional	50	200	300	40	896.595 [N]
19	Bell	Changed shape	50	200	300	40	565.489 [N]
20	Bell	Dual	50	200	300	40	906.699 [N]
21	Bell	Changed shape	50	200	300	40	1060.87 [N]
22	Bell	Changed shape	50	150	300	40	815.339 [N]
23	Bell	Changed shape	50	150	300	40	820.179 [N]

The data indicates that a larger throat diameter corresponds to a larger thrust output, however, it also increases the flow rate. The outlet diameter shows a similar relationship. The total length of the nozzle has been kept constant to ensure the weight of the nozzle is minimized and it occupies minimal space on the rover.

The boundary conditions were set as follows:

Table 1. Boundary conditions of the nozzle

Sr no.	Boundary condition name	Values
1	Pressure Inlet	3447000 Pa

2	Pressure outlet	0 Pa
3	Wall function	Stationary Wall; No Slip; Standard Roughness
4	Model Type	SST k-omega

The gradient for static pressure was extrapolated using the POST module within FLUENT on the workbench module of ANSYS, static pressure was selected as the study contour and the number of colors was set to 100 to ensure a smooth visible color transition on the study.

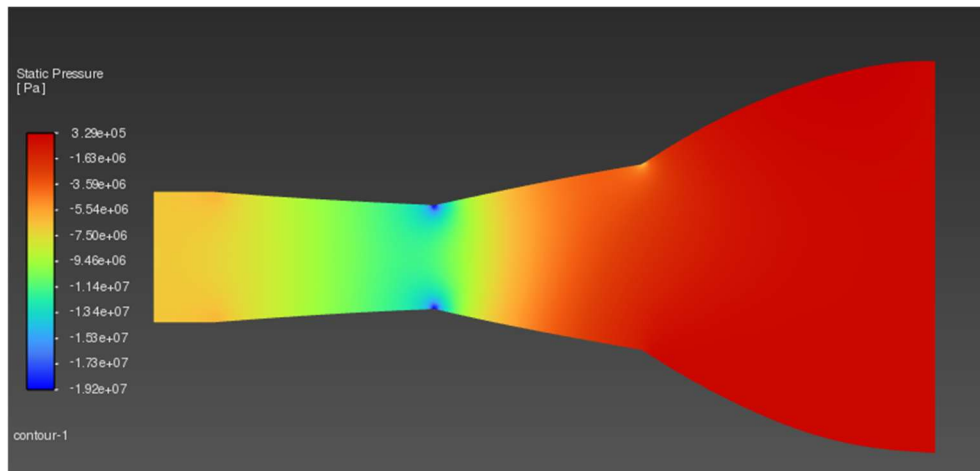


Fig. 4. Static Pressure Gradient of a Dual Bell Nozzle

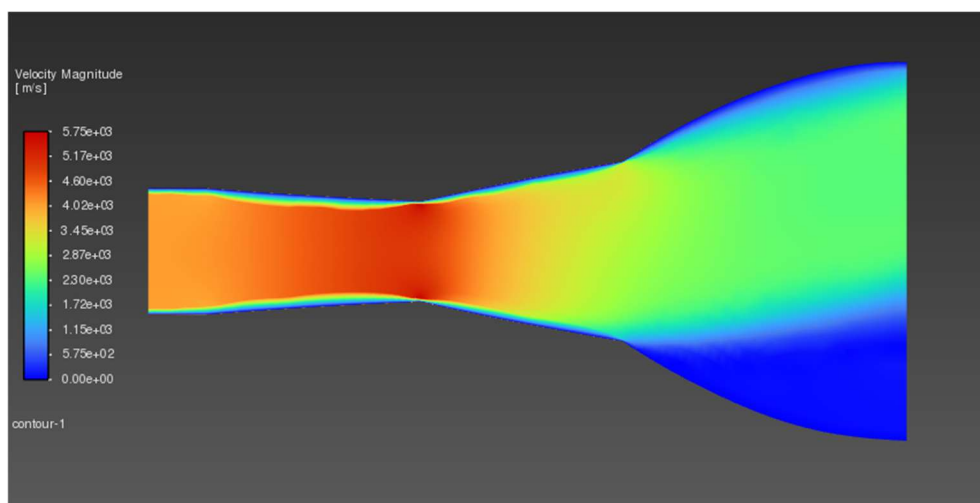


Fig. 5. Magnitude of Velocity Gradient of a Dual Bell Nozzle

An interesting and key observation was that nozzles with higher thrust outputs had greater static pressure near the outlet as can be seen in Figure 4, which represents the Pressure gradient of a dual bell nozzle with an output thrust of 820 N. Similarly, it was observed that

velocity of air particles increased at the throat of the nozzle and gradually decreased till the outlet in nearly all nozzles. This can be seen from Figure 5.

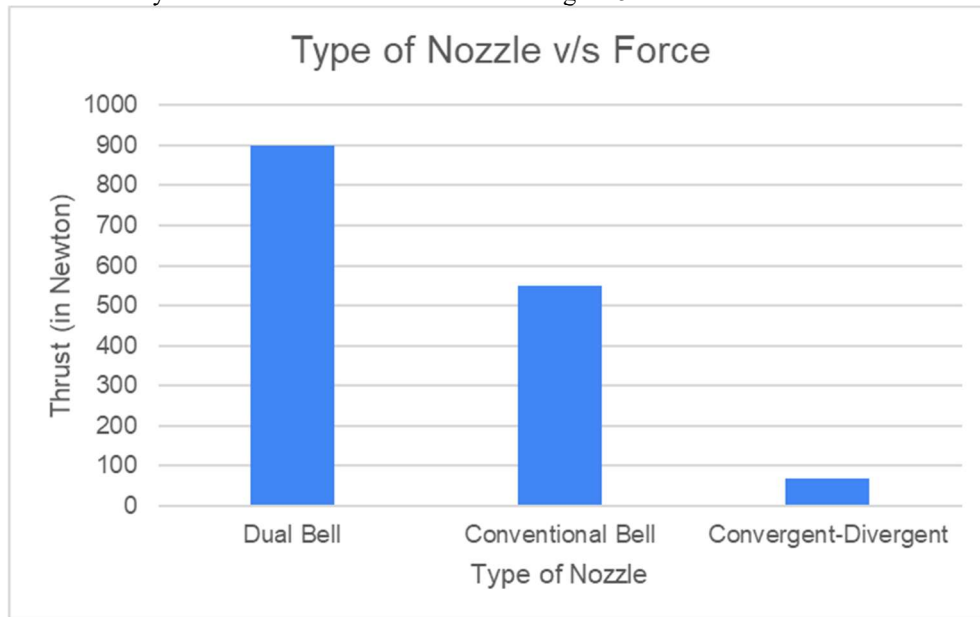


Fig. 6. Type of nozzle vs thrust they exert in Newton

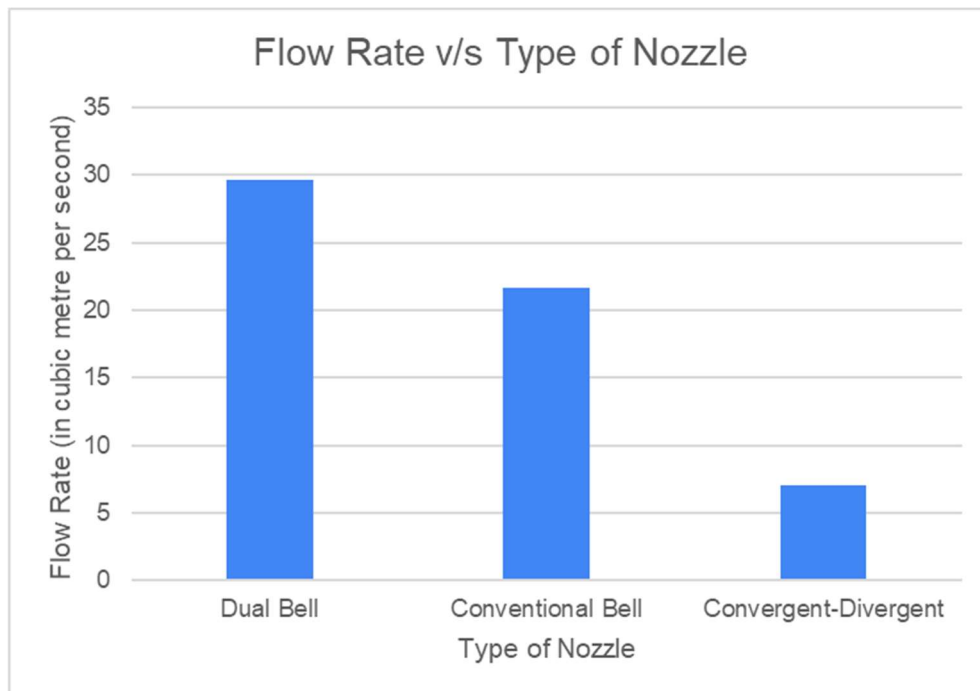


Figure 7: Type of nozzle vs the volumetric flow rate in m³/s

It was found that the dual bell nozzle geometry provided the most thrust, nearly twice that of conventional bell nozzles and ten times that of convergent divergent nozzles. However, they also had the highest flow rate of around 30 m³/s

Hence nozzle number 23 will be considered for the same, the same is chosen as this will provide a large amount of thrust while not consuming the pressurized air for a long amount of time, this nozzle can be controlled and turned on and off repeatedly such that lift can be generated in pulses without consuming the entire air tank at once preserving the air charge, taking all of the above data into consideration
Figure 6 and 7 represent the comparison between volumetric flow rates of the nozzles tested, the volumetric flow rate is directly proportional to the thrust the nozzle is able to produce and is an able representation of the same.

The Thrust Needed is $F = 485$ N, meaning the rover's weight on Mars is 65%.
The selected Nozzle flow rate has Nozzle 23, which has a flow rate of $Q = 30$ m³/s.
2 nozzles are used and therefore thrust $1 = 500$ psi = 820 N each at 2 nozzles and total thrust = 1640 N.
Ratio of 0.3 Thrust is required only from these nozzles therefore only 0.3 Q will be used.
To increase throttle = 8.9 m³/s.

$$Q \text{ final} = 8.9 * 0.3 = 2.67 \text{ m}^3/\text{s}$$

Supposing the first case where the thrust period of Electronics is $t = 3$ seconds, Air pressure exhaust which is required out of the tank: $P_{\text{tank}} = 500$ psi or $P_{\text{tank}} = 3447.375$ kPa.
Assumed ambient pressure: $P_{\text{ambient}} = 0.636$ kPa. (on martian surface)
 $P_{\text{storage}} = 10000$ Psi (pressure with in the storage tank)
Assumed average air temperature on Mars, $T = 210$ K.
The mass Flow rate of air m.

$$m = (Q \text{ final} / RT) * P_{\text{tank}}$$

where,

Q is the volumetric flow rate in m³/s, and

R is the specific gas constant for hydrogen = 4124 J / (Kg * K): T in Kelvin.

The result of the equations is $m = 212$ Kg/S air mass total is:

$m_{\text{total}} = m * t$ where t is the time of deployment.

Result = $m_{\text{total}} = 636$ KG

Volume tank v, using ideal gas:

$V = m_{\text{total}} * (RT / P_{\text{storage}})$.

Result: $V = 1.335$ m³.

After, a tank of volume 1.335 m³ will be used for discharge at nozzles within 3. Seconds.

4 Conclusion

This research illustrates the effectiveness and possibilities of using a thrust system that utilizes compressed air to assist planetary rovers in making a recovery after being immobilized like when they are submerged in sand or loose dirt. The study combines design, computer-based, and theoretical aspects to ensure that the system functions under extraterrestrial conditions.

Using the FLUENT module within ANSYS, computer simulations were performed using the computational fluid dynamics (CFD) technique that confirms the efficacy of multiple nozzle types when it comes to thrust, flow rate, and air efficiency. The analysis labeled nozzle 23 (dual bell nozzle) design as the most favorable since it was tested and confirmed to produce thrust for 906.7 N with a big air supply. The thrust exerted need not exceed 65 % of the rover's weight and is effective in making the rover recover from being immobilized, while the nozzles designed provide more than the projected figures. Important findings in the study cover the highlights of balancing nozzle designs so that the rover

produces adequate thrust while not consuming excess air. Results from the simulations' static pressure gradients and velocity contours serve as evidence that the Nozzles provide a respectable amount of thrust without consuming excess amounts of compressed air.

The key takeaways from the study conducted are:

1. Bell nozzles especially design 23 can generate thrust enough to lift the entire rover in the air
2. The bell nozzles display good flow with minimal chances of mass flow choking
3. Multiple nozzles can be placed to enable thrust vectoring capabilities to turn an overturned rover upright.

To integrate into rover designs, this system integration requires existing air tanks capable of performing above 500 psi. They also have to be airtight and easy to seal. Furthermore, the tanks have to be small enough to fit within the rover's structure and contain sufficient air to support multiple recovery attempts. The suggested modularity of the tank system ought to be sufficiently small to allow for potential refilling during subsequent missions while increasing the lifespan of the rover and reducing mission immobilization risks.

Future work includes prototype testing in simulated extraterrestrial environments to verify the CFD results. This will be done by testing the system against Mars' atmosphere, temperature, and even the dust that could block the nozzles. Additionally, efforts will focus on refining control algorithms for precise thrust vectoring and strengthening system components to withstand prolonged harsh conditions. Incorporating a compressed air thrust system allows emergency capabilities that enable overcoming obstacles that cause mission failure. With this solution, the current method is transformed.

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