

Advances in Rocket Propulsion Systems- A Comprehensive Insight on Design, Performance and Future Systems

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Abstract: Over the years, there have been significant advances in rocket propulsion system. These advances have been encouraged by the urge to improve reliability, efficiency and versatility in space exploration. This study provides comprehensive overview of those advances. It would be focusing on major breakthroughs for rocket propulsion systems and their effect on space missions. In rocket propulsion systems, recent advances cover different factors like engine systems, propulsion systems, control and materials. Some of the examples of electric propulsion systems are Hall and Ion effect thrusters which have transformed long-term missions by providing better fuel efficiency and impulse than conventional chemical counterparts. These systems have been widely used in deep space missions, orbit transfer, and keeping satellite station. In addition, developing engines, combustion technology and smart propellants have advanced traditional chemical propulsion. 3D printing and other technological breakthroughs have enabled production of complex engine parts with better effectiveness and accuracy. It has reduced expenses and improved performance. In addition, researchers have advanced reusable techniques to improve availability of space and reduce launch expenses. As observed by launch of reusable vehicles by several aerospace organizations, major achievements have been observed in reusability of engines, landing, and thermal protection. In addition, ambitious missions have been achieved with advances in rocket propulsion systems, including lunar exploration programs, manned Mars expeditions, and asteroid mining operations. Rocket propulsion systems are needed for covering long distances with spacecrafts and achieving objectives of mission. In rocket propulsion systems, recent advances have exceeded the boundaries of space exploration, offering unmatched potential for corporate ventures and international cooperation.

Keywords: Rocket Propulsion Systems, Space Exploration, Aerospace, 3D Printing, Thermal Protection, Landing.

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I. INTRODUCTION

Satellites are very important to promote navigation, communication, scientific research, Earth observation, and weather forecasting in modern world (Venkatesan et al, 2013). However, permanency and efficiency of satellite missions depend majorly on propulsion systems for orbital maneuvers, controlling altitude, and holding orbit. Legacy chemical propulsion systems have been widely used for propulsion but they have high mass and limited fuel capacity with poor efficiency (Sonko et al, 2024). Electrical propulsion has come as a better alternative to chemical counterparts. First, they use solar power from onboard panels for long-term and efficient propulsion without limited and heavy chemicals (Sonko et al, 2024).

Electrical systems go beyond lifetimes of satellite mission as they can work for longer periods, improve maneuverability, and longer missions. Secondly, there are higher “specific impulse (ISP)” provided by electrical

propulsion in comparison to chemical propulsion, causing lower consumption and higher velocities for similar delta-v needs (Nardini et al, 2020). This benefit of efficiency reduces cost and launch mass, making electrical propulsion especially appealing to interstellar exploration and small missions as well (Etukudoh et al., 2024).

Rocket engines act as the key factor that drive space exploration. Spacecraft use those engines to propel and explore farther distances and celestial bodies in outer Earth orbit. Over the years, significant advances have been achieved in rocket propulsion systems, encouraged by improved efficiency, performance, and lower prices. Rocket engine propulsion supplies fuel to the engine and it is burnt to build thrust. There are several elements in the system, such as, fuel, propellant tanks, oxidizing systems for agent delivery, supply circuits, and control systems. It is aimed to ensure dependability, stability, and efficiency of operations.

Structural loads are highly prevalent in missions against propellant supply systems, which require complete structural research to verify and authenticate its integrity (Nenciu et al, 2023). Sometimes propulsion systems may use electric equipment for power, engine pumps, and control units, while amassing devices like supercapacitors or batteries in accumulator. These components enable constant activation, cavitation control, and improved control over thrust vector (Sutton, 2003). The key here is to reduce several pipelines, weight, and overall construction, while also minimizing losses of pressure in oxidizing agents and fuel flow in propellant supply (Sutton, 2003).

In addition, exhaust gas circuit can improve the propellant tank pressure when it comes to relieve combustion chamber off exhaust gases (Mishra, 2017). Several propellant storages are connected by control valves in some rocket engine systems to add extra propellant without losing capacity (Mishra, 2017). The propulsion system in the rocket engine works by combining combustion with liquid propellant to build thrust. The system consists of rocket engine which gets propellant, propellant tanks, and control system. The liquid propellant is expelled by an injector core to generate combustion gas through the structure of the pump (Shin, 2022).

Known for its spherical shape, the combustion chamber covers combustion area and it is directly open to the gas (Holder et al, 2023). Located ahead of the outlet, the propellant injector releases chemical propellant into the interior of the engine (Sakaguchi et al, 2019). A turbopump is propelled by the flow of combustion gas to deliver oxidant and fuel to the combustor and pre-burner (Mishra, 2017). In addition, exhaust gases are shifted by the circuit from the combustion chamber to the tank to elevate their pressure. Several propulsion technologies are used by rocket engines. Electric motors are used by propulsion system variant for propellant pumps for increased reliability and activation in managing thrust vector (Sutton et al, 2026). A system with propellant injector and combustion chamber is another variant sending cooling fuel through the wall of the chamber (Holder et al, 2023).

In addition, some systems use, ignition unit, hydrogen supply, and oxygen supply systems to ignite the blend of hydrogen and oxygen within combustion chamber (Gotzig et al, 2021). In addition, electric motor system acts as an essential source of power for removing, adjusting, and starting thrust and changing settings in operations to reduce the workload for the motor (Gotzig et al, 2021). Several applications of rocket engine can use these diverse approaches related to propulsion offering different perks. There are several benefits and challenges of rocket propulsion system which vary on the basis of specific kind of system used. Hybrid and gel-based propellant systems reduce hazard, ease handling properties, and add variable thrust when used with right propellants (Ciezki et al, 2017).

Thrust vector systems can control the flight when combining gas-dynamic and mechanical systems, including “Bifunctional Thrust Vector Control System (BTVCs)”

when combining gas-dynamic and mechanical systems. It can add a lot of control forces with superior performance and reducing loss of specific impulse (Strelnykov et al, 2013). A cooling duct is used in another system for propulsion control to manage the flow of hydrogen, oxygen, or a blend of combustion gases in the chamber to improve the efficiency of the system (Gotzig et al, 2021). Further, a liquid gas tank is used by rocket propulsion system to reduce the need for individual pumps to manage the fuel and oxidizer to improve efficiency and reduce complexity (Aueron and Thomas, 2022). Ignition system and injectors are used by rocket propulsion system to ensure uniform flow of fuel and oxidant across the ignition and injection stages to improve combustion (Aueron and Thomas, 2022).

In addition, thrust control is more precise and smoother in electrical propulsion system, with maneuvers and orbit changes accurate enough for formation flying and deploying constellation satellites. Existing propulsion systems cover different approaches like thrusters of hall effect, ion propulsion, and pulsed thrusters. Ion propulsion systems use electromagnetic/electrostatic acceleration of ions like xenon-based thrusters (Hamdan et al, 2024). Ion thrusters can deliver low thrust with high efficiency over longer period of time and they also have challenges like long time for acceleration and low levels of thrust, which can affect their use of large maneuvers or rapid changes in orbit. Hall effect thrusters accelerate plasma to promote higher thrust with a magnetic field in comparison to ion thrusters, while holding ideal efficiency (Atadoga et al, 2024). There are still several challenges about possible degradation of efficiency and removal of channel of discharge over time. Pulsed thrusters build thrust when plasma is ejected with a range of hidden pulses, adding thrust at the cost of shorter operations and lower efficiency because they remove electrodes (Abatan et al, 2024). While capabilities have been enhanced in these technologies for satellite propulsion, there are several challenges like mass limitations, limited thrust, lifespans, and need for more research.

In electrical propulsion, this study explores future potential to address the challenges of existing propulsion systems and unlocks new possibilities for conducting space missions. Advanced concepts like variable-based rockets and magneto-dynamic thrusters add higher thrust, efficiency, and acceleration in comparison to current technologies. The performance of electrical propulsion is further improved by improving efficiency and miniaturization to reduce mission expenses and integrate into smaller satellites. In addition, research on sustainable propulsion like propellant alternatives and solar propulsion can reduce carbon footprint of satellite missions and space exploration can be more sustainable in the long run. This study explores future prospects in satellite industry to push the boundaries for future missions.

II. REVIEW OF LITERATURE

Conventional liquid propulsion systems rely on oxidizer and liquid fuel as propellants. All major space missions have used liquid propulsion systems since the

beginning of space race. The flow of propellant is regulated by well-synchronized parts of those systems. These systems transport the liquid to needed pressures and inject the same to combustor (Evulet, 2016). They should consider several factors like cryogenics, propellant selection, engine cycles, performance, liquid propellant, supply systems, thrust chambers, turbopumps, and eccentric engines. They are highly interlinked in both liquid and mechanical perspectives (Zeng et al, 2014).

In the futuristic spacecrafts, the performance of liquid propulsion spacecrafts will define the failure or success of the mission (Rosen et al, 2003). There have been significant improvements observed in traditional liquid propulsion systems. Engines are classified by propellant combinations, applications and engine cycles in the dominion of rocket engines. Researchers have tested, flown, and studied several blends of propellants (Domić et al, 2022). Table 1 lists recent works on traditional systems.

Table 1 Recent Developments on Liquid Propulsion Systems

Authors	Findings
Cho et al (2016)	Combustion engines and aluminum solid loading suffer a lot by rationalized gas generator cycles.
Elbasuney (2019)	Hydrazine fuel burns better with aluminum particles. Six weight percent is the ideal solid loading.
Bechasnov (2022)	Enough power can be generated by hybrid and micro rocket motors. There is enhanced safety in production and operation.
Trinh et al (2003)	Introduced the concept of vortex chamber to improve combustion. Demand for cooling is reduced by passing the cooler streams through the chamber wall.
Bao et al (2022)	Cost and time can be reduced significantly with 3D printing. It is especially beneficial for liquid engines. However, there are still challenges like material, size range, and rough surface.
Kozlov et al (2011)	CCCM is used by small rocket engines in the chamber. A reliable connection was built for engines to mix metals.
Chandler et al (2012)	Impression regression was observed in paraffin fuels for hybrid systems. Liquid layer was observed in combustion, which causes high mass transfer.
Satyaprasad et al (2017)	Propulsion system included scramjets and liquid/solid-fuel rockets.

The key component of space vehicles and ballistic missiles, liquid rocket engines have come a long way in space exploration, such as, visits to outer Earth orbit and the moon (Filippone, 2022). The transportation of liquids in the marine sector has progressed from using drums to integrating tanks into structures of the ship (Kim et al, 2010). Propulsion systems have been created with technological advances for tankers working in ice conditions, including, electrical propulsion with controllable- and fixed-pitch propellers and podded ones (Wilkman et al, 2018). With these advances, tankers can

work in various areas and show better performance on ice (Sloop, 2014).

One of the most well-known forms of liquid propulsion, internal combustion engines affect the environment. Modern characteristics like hybrid engine and electric motors have gained a lot of attention by increasing efficiency (Zhao, 2023). Figure 1 illustrates places where vibration and noise could come out of aft-mounted fan (Filippone, 2022).

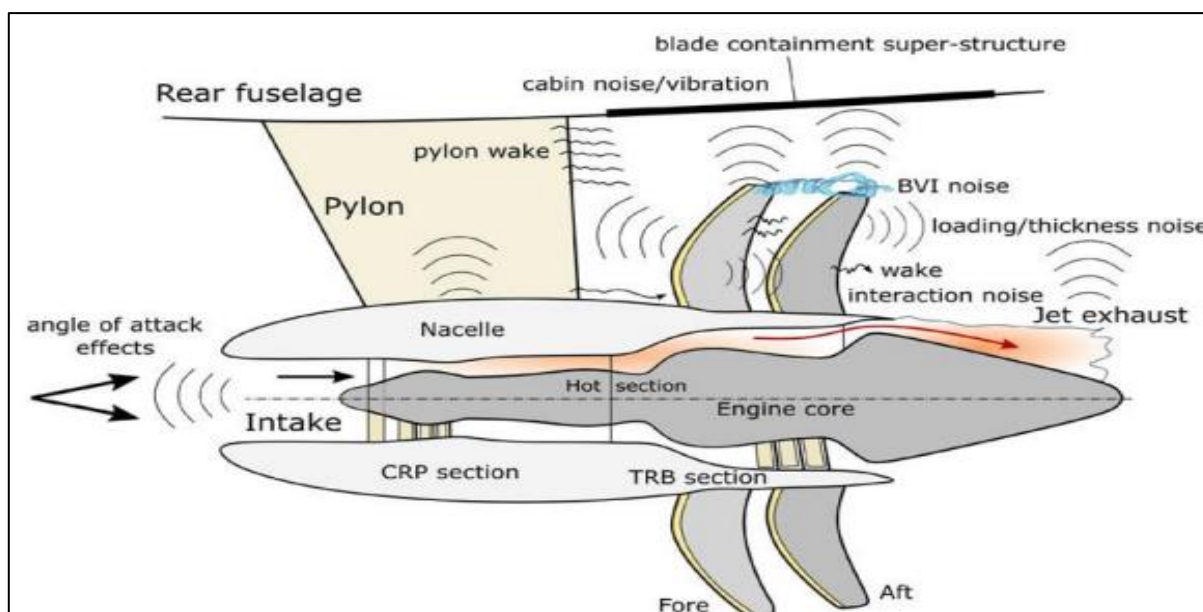


Fig 1 Vibration and Noise Sources on Aft-Mounted Fan
Source – Filippone (2022)

There are several benefits of electric motors like strong performance, affordable maintenance cost, efficiency, and minimal emissions (Pan and Zhou, 2023). There are some drawbacks too, such as, no charging infrastructure and low range (Dai and Ye, 2023). Propulsion systems must be compared with aspects like cost, power, range, and carbon footprint (Mejergren, 2014). There are still several issues in electric propulsion systems like range and energy density

(Crespo et al, 2014). Considering all positives and negatives, the future is still bright for alternative propulsion systems, with constant advances in terms of affordability and electrical parts. In the operation and design of traditional liquid propulsion systems, following environmental standards and reducing carbon emissions are very important (Zhang, 2012; Inal, 2022). Figure 2 illustrates comparison of converted and unconverted torque (Pan and Zhou, 2023).

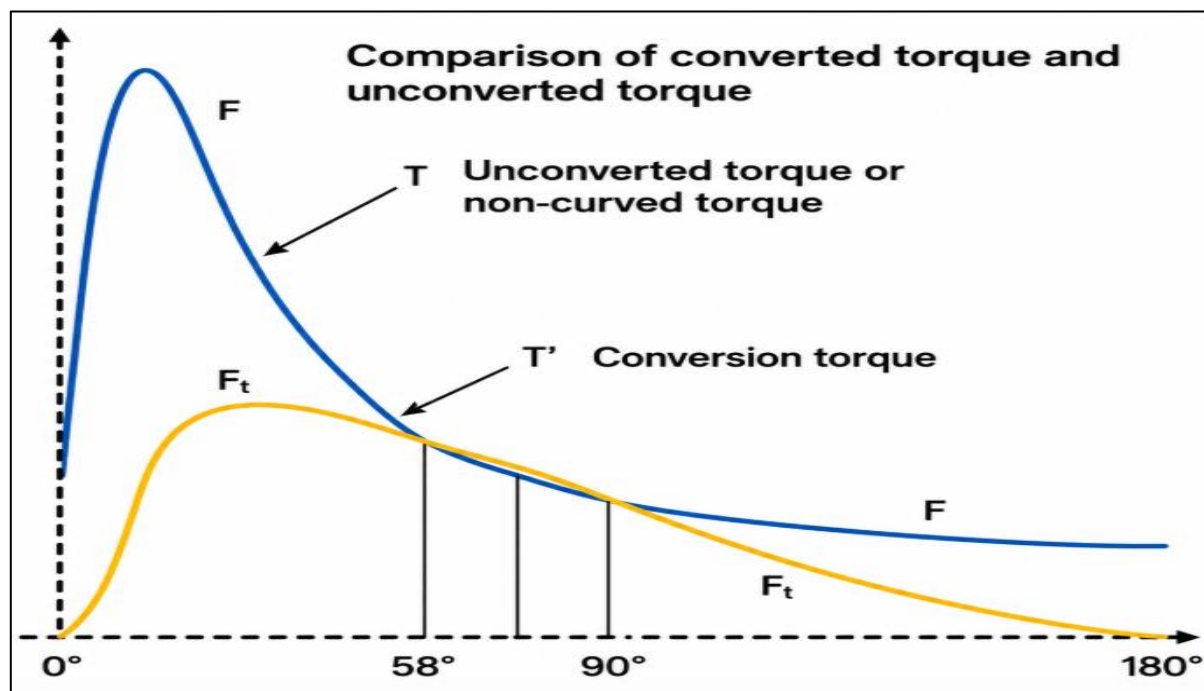


Fig 2 Comparison of Converted and Unconverted Torque
Source – Pan and Zhou (2023)

More efficient and greener power systems are needed like sourcing energy with the use of electricity (Senda and Harumi, 2018). To reduce carbon emissions and comply with regulations, ships should also improve energy efficiency and minimize effect on the environment (Keese, 2022). It is also expected that innovations will generate new financial opportunities in marine systems and play a vital role in greener future (Emdee, 2010). Along with providing solutions for several dynamic issues in building engine, there are several dynamic challenges in thrust liquid engines (Huang et al, 2019). To reach zero-emission goals and reduce emissions, it will be required to develop modern technology like alternative fuels and hybrid propulsion systems.

III. METHODOLOGY

➤ Research Design

This study is based on exploratory and descriptive research design which is solely based on secondary data. Descriptive research design is adopted to systematically present recent developments in rocket propulsion systems, such as, operational performance, design principles, applications, performance, and technological advances. Exploratory research design seeks to explore the concepts of propulsion systems, research gaps, innovations, and future directions to transform spacecrafts. This approach is ideal

with constant rise of rocket propulsion with rapid advances in reusable systems, efficiency of propulsion systems, 3D printing, advanced materials, sustainable technologies, and electric propulsion. The study provides in-depth understanding with critical analysis of existing studies on rocket propulsion system.

➤ Data Source

The study is based completely on secondary data sources like articles published in peer-reviewed journals, books, patents, research papers, technical reports, and conference papers published by academic publishers and aerospace leaders. Special emphasis was given to address advances in electric, liquid, solid and hybrid propulsion systems, along with developing recyclable launch vehicles, sustainable technologies for propulsion, and advanced manufacturing system. With secondary data collection, diverse perspectives are collected with wider knowledge on rocket propulsion developments.

➤ Data Collection

For data collection, relevant studies were screened as per their abstracts, titles, and keywords. In addition, data was collected from each study based on operating principles, types of rocket propulsion system, thrust, impulse, propulsion performance, materials, fuel efficiency,

applications, manufacturing techniques, future advances, and limitations.

➤ *Reliability and Ethical Considerations*

To ensure reliability and validity of study, data was verified across various technical reports, peer-reviewed studies, and authoritative publications related to aerospace. Recent scientific studies were preferred while incorporating studies which contributed majorly to the rise of rocket propulsion systems. Findings were compared from different sources to reduce the risk of bias. When it comes to ethical considerations, this study is completely based on secondary data, which is available on public domain. This study also doesn't involve experiments, human participants, or confidential data. All the original sources are mentioned with references and citations as per the recognized standards.

IV. RESULTS

➤ *Solid Rocket Propulsion System*

Solid rocket propulsions play a vital role in the fields of defense and aerospace. The propellants are the key for space exploration activities like interstellar travel and satellite launches, along with military missions, especially for developing missiles (Mason and Roland, 2019). Their significance is based on their potential to generate high levels of thrust in a compact and stable system. Solid propellants are known to be easier to handle and store, which makes them ultimate and reliable option for multiple use cases (Davenas, 2003). Usually, a solid rocket propellant consists of oxidizer, fuel, and binder.

The fuel provides maximum energy, binder contributes to overall energy by combining three key ingredients, while oxidizer helps in ignition by providing needed oxygen (Kuentzmann, 2002). However, oxidizer significantly programs the burn rate, efficiency, and other characteristics of performance in the propellant. Ammonium Perchlorate (AP) is an oxidizer used in solid propulsion systems as it balances economy, performance, and stability (Beard, 1992). It has been applied most widely for both military and civilian rocket formulations as it has high amount of oxygen, which supports long-term and rapid combustion (Zhu et al, 2014). AP also remains stable under normal situations, making it reliable and safe for use in the long-term in solid formulations.

It is also leading in the oxidizer segment due to its affordability. The propellant based on AP is made of around 15% of "hydroxyl-terminated polybutadiene (HTPB)", 70% of AP, and aluminum has around 20% of weight (Jain et al, 2009). There are still several issues of AP-derived propellants, such as low burning rate, which could affect the thrust (Ramakrishna et al, 2006). While the thermal decomposition is fine and stable under ideal situations, there are challenges related to low combustion due to high temperature. The combustion of AP also releases toxic gases to the environment, which affects biodiversity by leading to acid rain (Urbansky, 2002).

With the rising focus on sustainability in the environment, there is a rising demand to reduce HCl emissions. Solid rocket propellants can also adopt nanotechnology to improve performance, i.e., by using nano-additives. Performance can be improved with nano-scale particles added to the propellant (Abrukov et al, 2019). Those additives have microscopic dimensions that cover larger area due to their distinct physical and chemical properties. In solid rocket propellants, there are several benefits of nano-additives, including higher release of energy, more efficient combustion, adjusting the burn rate, and higher thermal stability to improve performance (Aziz et al, 2015).

The overall combustion is also improved by nano-additives, while elevating net energy output (Pang et al, 2021). In addition, additives can minimize the energy needed to activate ignition with high reactivity. It can save time to release energy and ignite with the propellants. AP combustion emits these additives to react with emitted HCl to release fewer toxic compounds and neutralize them (Ashraf et al, 2024). Carbon nanotubes (CNTs) have several useful features and exceptional structure which gained a lot of scholarly attention worldwide. CNTs can alter the burning speed and combustion behavior of "solid rocket propellants (SRPs)".

These nano additive properties make them great choice for next-gen formulations to provide maximum output (Pang et al, 2023). With lower iron oxide, graphene oxide, and "covalently modified graphene oxide (CMGO)" improve combustion efficiency in solid rocket propulsion systems. Their surface area is large and functional groups are rich in oxygen to improve dispersion in the matrix by boosting oxygen release (Kumar et al, 2017). The $\text{Fe}^{3+}/\text{Fe}^{2+}$ cycle increases flame temperature having effective redox of FeO_3 nanoparticles, which reduce the energy barrier and strengthen exothermic reactions for decomposing AP, which lead to the rise in burning rate.

Meanwhile, the dispersion is stabilized by rGO, which improves electron mobility and thermal conductivity, improving electron transfer and heat transfer during combustion (Chaudhari et al, 2024). These additives increase the release of heat, reduce decomposition, and boost burning rates, increasing eco-friendliness and efficiency of propellants. The AP breakdown is altered by some nano-additives to improve the release of energy for performance benefits (Azizi et al, 2025).

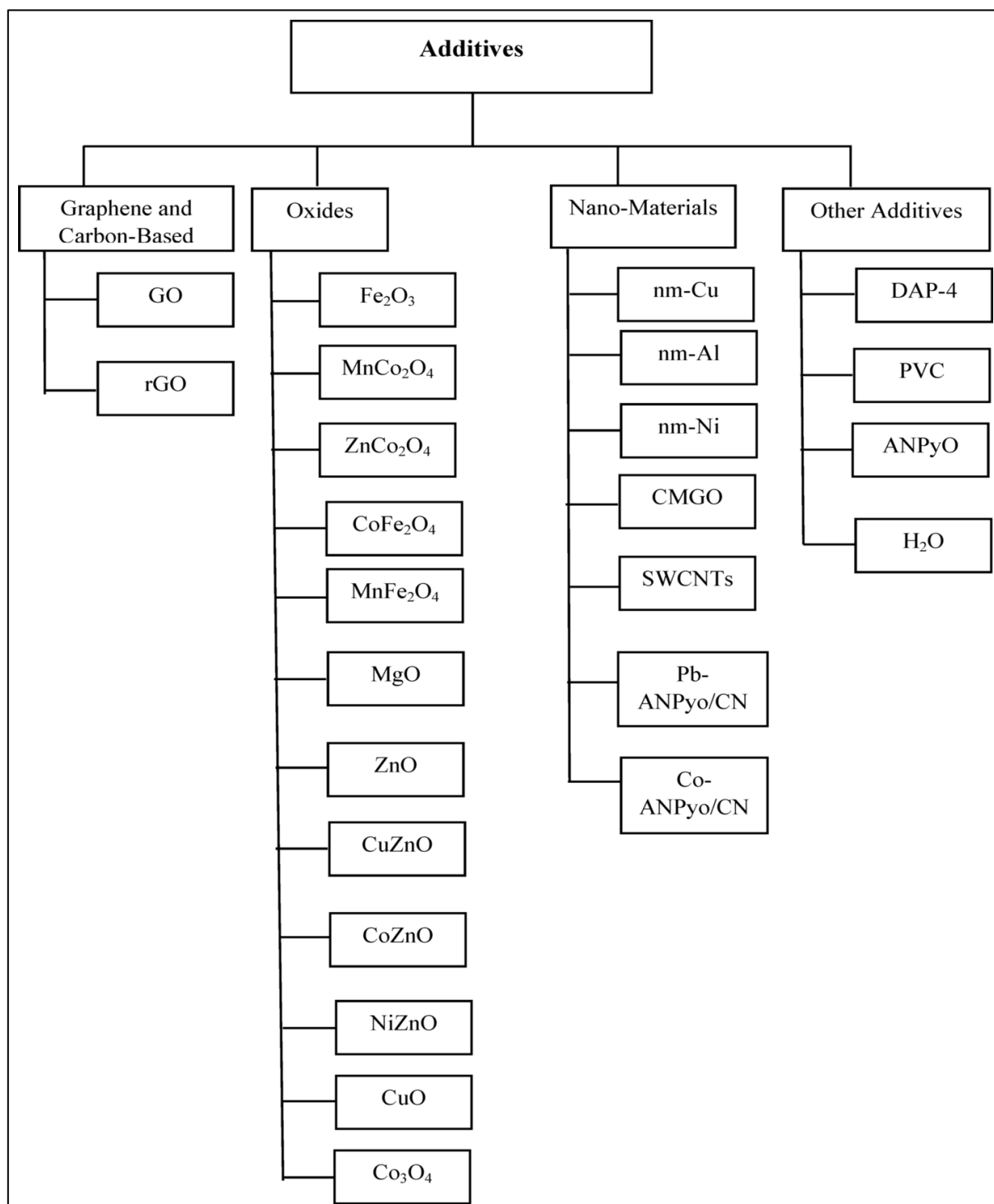


Fig 3 Release of Various Nano-Additives or Metal Oxides

Source – Kumar et al (2025)

The synergy between nano-additives and ammonium perchlorate is the most promising direction for research (Sang et al, 2021). Having nano-sized additives in AP-based propellants changes the combustion and decomposition behavior (Trache et al, 2017). For example, the thermal decay of ammonium perchlorate is another major concern due to lead nanoparticles or metallic nano-additives, while improving oxygen velocity and combustion efficiency (Zheng et al, 2018; Pandas and Fazli, 2022). Along with

rocket thrust, it also adds control over the profile of energy release and burn rate, which are vital for rocket propulsion.

Thermal stability may be improved further with nano additives in propellants, while minimizing the risk of thermal release or early ignition, which affect propulsion systems (Petersen et al, 2019). Figure 3 illustrates the release of nano-additives with the use of AP for solid rocket propulsion systems.

➤ *Electric Propulsion System*

Given that chemical propulsion systems are highly reliable and simple in design, the question is still the same – why electric engines should be used when they are hard to use? In spaceflight, launches and cost of building a spacecraft are the major factors. There are two factors considered to minimize per kg cost of cargo flights – reducing number of launches and reducing cost of each launch (Bezyaev and Stoiko, 2018). Liquid and solid propellant engines are used in first stage and have truly high thrust because their impulse is relatively low. They can achieve speed of orbit and cargo is placed in orbit of Earth.

Meanwhile, low thrust is needed in majority of deep space missions, while higher impulse thrust is needed to minimize the spacecraft position. In addition, interstellar missions usually need higher propulsion than launch vehicles. There is a need to combine electric/chemical propulsion for these missions. Usually, solid/liquid fuel is used by chemical rocket engines for propulsion. Fuel consumption and chemical energy are used to determine the energy leaving the rocket, which is the key issue of chemical rockets (Fearn and Martin, 1995). More powerful pumps, larger rockets, and more fuel are needed for long-duration flights which need higher costs.

The situation is totally different with electric motors. Electric rocket propulsion systems work on electricity, which can be generated by onboard nuclear power plant or solar panels, where initial mass is not much required and this motor can run consistently for several hours. Electric traction is highly stable and this system is more reliable and efficient as compared to chemical engines. Chemical fuel can also be replaced by electricity for research in Earth orbit, which affects mass ratio of LV to minimize cost. For long-distance missions, using such fuel can be justified. This fuel is best suited for interstellar missions without human intervention. Hence, interstellar space flights in automatic mode can be planned well for deep space exploration (Bezyaev and Stoiko, 2018).

• *Use of Electric Propulsion in Spaceflight*

In space missions, using and developing electric propulsion is expanding rapidly and its benefits are constantly rising. John Brophy (2022) explained the use of electric propulsion system in different government and commercial missions out of his experience of 40 years in electric propulsion at Jet Propulsion Laboratory, NASA. According to him, electric propulsion systems could be used from small satellites in LEO to deep space missions. Over time, this system will infuse all areas of exploitation and exploration of space technology.

Some studies have also explored the challenges of electric rocket systems for different purposes. Abbasov and Nosrati (2023) proposed plasma rocket engines working on thermonuclear fusion. Their concept could be beneficial for using electric engines in future explorations. Thermonuclear and nuclear rocket engines are more beneficial to explore deep space irrespective of some risks. Sinyavsky (2020) proposed the development of Energia rocket and stages of

building a “magneto-plasmodynamic” engine with a lithium fluid to generate 500 to 600 kW of power. The thrust density of those engines is highest and more efficient than other engines (Abbasov and Nosrati, 2023). The overall performance is still relevant in this engine.

Gorsgov et al (2008) proposed ion plasma engines and development of Hall for different purposes as part of spacecraft. They described the features and designs of those engines as per experimental research. Abbasov and Nosrati (2023) described the use of electric propulsion system for adjusting spacecraft position. They classified modern electric propulsion systems like electrostatic, electrothermal, magneto- and pulse-plasmodynamic engines. They also defined their technical specifications – impulse, thrust, power efficiency, and consumption. They noted the problems in their future use for fixing the orbits effectively. Ageev et al (1977) used laser rocket engines for near-space exploration. This kind of engine can be both cost-effective and can be used for launching small spacecraft to solve the existing challenge in destruction of space debris (Pelton, 2013). Rezunkov (2007) noted the levels of developing laser-based engines and Phipps (2018) presented the experimental application of the same for foreign and domestic research.

Electric propulsion system consumes much less fuel in spacecraft and satellites in comparison to their chemical rocket counterparts. With electricity, spacecrafts can cover longer distances for longer period (Cassibry et al, 2015). They also add precision to control the path and trajectory of the spacecraft to maintain the satellite on the orbit and avoid crashing with debris or other objects. Electric motors can also enable spacecrafts and satellites to get back to earth and change orbits. They also reduce space pollution by reducing debris as compared to chemical fuels which pollute the outer earth orbit.

• *Electric System Composition*

For rocket engines, electric systems use electricity for propulsion of spacecraft. There are different types of systems – magneto plasmodynamic, electrostatic, pulsed, and electrothermal thrusters (Zhou et al, 2022). Usually, they have components like turbines, electric pumps, motors, and gas generators, working together for thrust to generate gas with high pressure (Mazouffre, 2016). In these systems, electric drives ease control, reliability, promote rocket recovery, and minimize battery weight (Tripathy, 2020). There are different features of thruster systems like thrust cost, certain impulse, and high efficiency, enabling selection on factors like cargo weight and power budgets for mission-specific selection. Overall, electric propulsion has been a great invention for space exploration, which adds efficiency and versatility for different space missions.

In rocket engines, there are different types of electric propulsion systems, such as, electrostatic, electrothermal, magneto-plasmo-dynamic and pulsed thrusters (Tripathy, 2020; Mazouffre, 2016). Hall and ion thrusters, Arcjets, Resistojets, and Field emission thrusters are some of the examples of these systems (Chopin et al, 2012). In

addition, innovative designs like highly efficient plasma thrusters, Electro spray and Colloid thrusters, and VASIMR are some of the examples of this range (Rachov et al, 2013). These systems vary in distributing kinetic energy to propellant with factors like thrust expenses, type of propellant, and certain impulse.

Selection of propulsion system relies on mission needs like simplicity, power requirements, and cargo load. It sheds

light on the flexibility and versatility of electric systems in spacecrafts. There are several benefits of electric propulsion systems over chemical counterparts in terms of carbon footprint, efficiency, and future trends. Hybrid and fully electric propulsion systems are compared in studies to suggest the benefits of turbochargers and recovery of waste heat (Altosole et al, 2022). Figure 4 illustrates the composition of electric rocket propulsion system (Zhou et al, 2022).

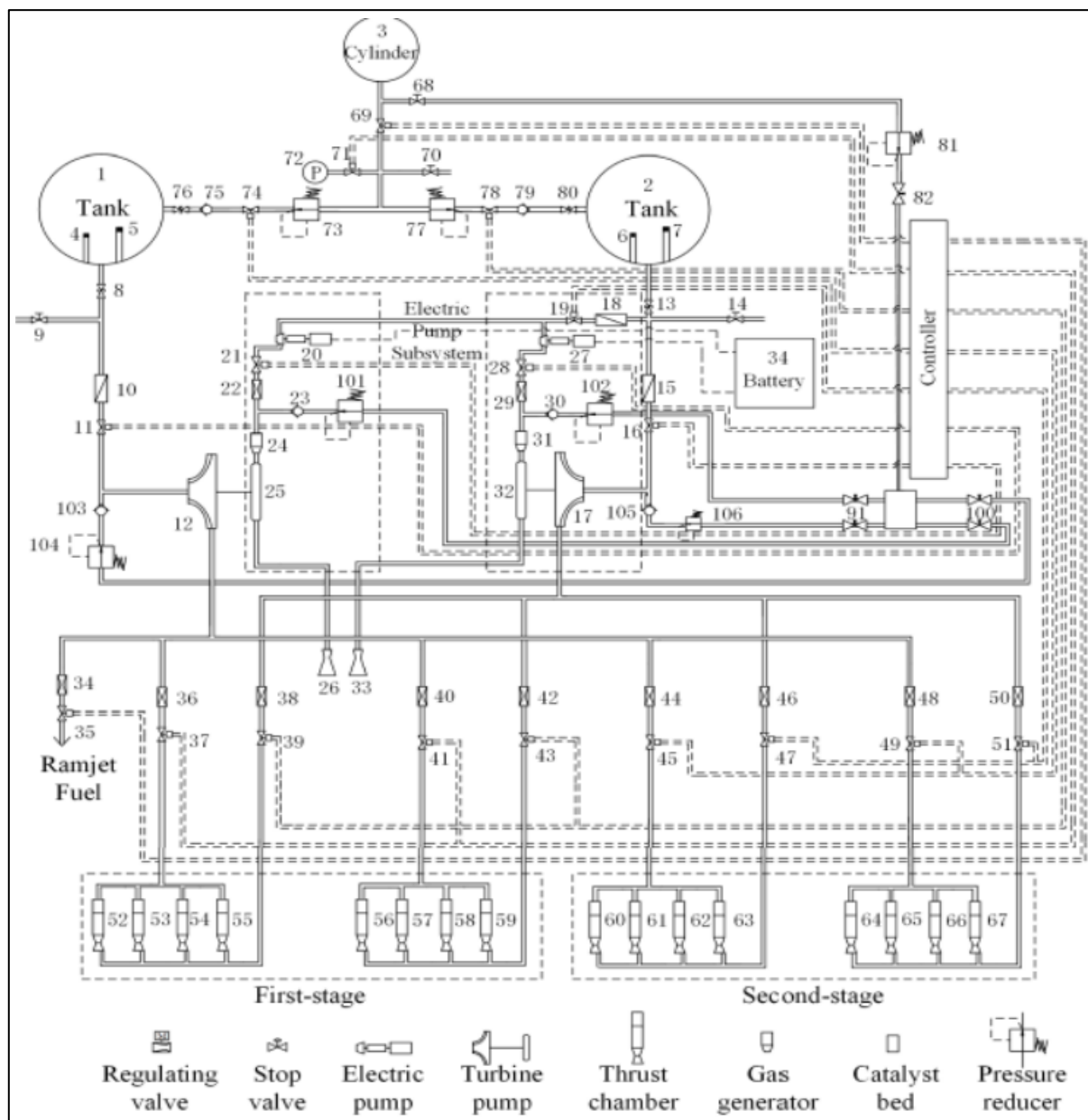


Fig 4 Composition of Electric Rocket Propulsion System

Source – Zhou et al (2022)

In addition, advances in electric systems are of different types like electrostatic, electrothermal, and electromagnetic, adding flexibility as per mission needs (Gao et al, 2023). In electric propulsion, novel designs improve environmental efficiency, with systems generating thrust with electric capacitors (Tripathy, 2020). Irrespective of challenges like limitations related to size and mass, there is ongoing research on minimizing the dimensions and

weight of electric systems, focusing on the need for connected generators for enhanced compatibility and performance (Goebel et al, 2023). Overall, electric propulsions are highly reliable and safe to maneuver in comparison to chemical propulsion counterparts (Batrak et al, 2022).

Technologies like electrical turbopumps having coolant ports, motor-driven systems for adjusting thrust and control, and high-speed pumps are some of the advances in electric propulsion (Beck et al, 2021). These innovations are required for improving performance, reliability, and efficiency, while minimizing overall engine regulation and system mass. In addition, lasers can be used to increase fuel efficiency and thrust in rocket propulsion, while focusing on practical approach, simplicity, and cost-effectiveness (Dyble, 2023). Developers are constantly looking for different approaches and technologies to improve safety and performance of rocket engines powered by electric systems (Walker, 2018).

V. DISCUSSION

There are different applications and future avenues for rocket propulsion systems. There are also several benefits of electric space thrusters over chemical ones, enabling longer lifespan of missions with propellant feeding and lower weight (Surmacz and Rarata, 2009). High energy propulsion systems are looking for new avenues and using ramjets,

turbojets, and scramjets for efficient access to affordable space (Daidzic, 2011). Cutting-edge rocket propulsion systems are widely deployed to minimize cost, improve performance, and ensure safety and eco-friendly nature of technology (Surmacz and Rarata, 2009). ML is widely applied to rocket propulsion to improve forecasting and performance (Ciezki et al, 2019). Hybrid propulsion is being popularized for different areas like satellite maneuvers, space tourism, and planetary landers for its regenerative braking, safety, and harmless propellants (Maicke, 2023).

Together, these advances redefine the future and current scope for rocket propulsion technology. These systems improve innovation, performance, and reliability. Propulsion can be improved with specific impulse, thrust, and constant burning while covering the topic of solid and liquid and solid propellant tracking (Davenas, 1993). The overall performance of heavy launch vehicles can be improved by adding booster and propeller weight (Salgado et al, 2018). Table 2 lists recent works and future directions on rocket propulsion systems development.

Table 2 Overview of Recent Works and Directions

Recent works	References
Efficiency of propulsion approaches under certain conditions. There are benefits and current prospects of multistage rocket vehicles to improve technology.	Liang (2022)
Improper combustion and impulses with mixture of water and aluminum.	Sundaram (2018)
Burning sources of solid fuel, while focusing on 2-stage flows, radiative effects and turbulence in inner ballistics	Fabignon et al (2016)
Hypergolic and liquid gelled bio-propellants are created for LPE. Effective management of combustion is achieved with excellent performance of ISVE engine	Nusca and Michaels (2006)
High-thrust engines achieved benefits like lower costs, less weight, and thermal stability	Herbertz et al (2012)
Liquid rocket engines were used with SiC matrix can enhance efficiency of engine. Turbine heat can be improved to boost impulse and minimize consumption of propellants.	Henson et al (2023)
In electric propulsion, future studies would be focusing on predictive modeling, testing accuracy, and realization of performance for different approaches	Dale et al (2020)

In rocket propulsion systems, current advances are exploring laser, nuclear rocket, and electric engines apart from traditional solid, hybrid, and liquid propellant systems (Lazareva et al, 2019; Remissa et al, 2023). Studies have developed more eco-friendly and efficient propellants to replace harmful options like green propellants like hydrazine and ammonium perchlorate (Teasley et al, 2023). NASA is constantly investigating detonation engine for interstellar missions to improve efficiency and compact designs for Mars and Moon missions (Liang, 2022). Furthermore, a chemical propulsion system was developed by Ariane Group for Jupiter and Moon missions to address issues like classifying hydraulic system and radiation protection. These advances improve propulsion safety, versatility, and efficiency for future missions related to space exploration.

The efficiency of rocket propulsion system is peaked under certain situations, given the factors like payload, cost, and thrust: weight ratio (Liang, 2022). Usually, these systems consist of propellant injectors, combustion chambers, and cooling for best performance (Gotzig et al, 2021). Rocket propulsion can be different on the basis of operation modes and propellant, adding flexibility in

operation and design (Gotzig et al, 2021). While rocket propellant is known for high energy needs to launch from surfaces, solar or electric engines are being tested for uses in future satellites. In terms of cost-efficiency, rocket propulsion systems deliver high thrust for space exploration. But there are high carbon footprint and propellant expenses, making it important to research and improve overall sustainability and performance.

For rocket propulsion, future studies may focus on advances in reusable systems like Blue Origin and SpaceX Falcon (Bechasnov, 2023), exploring innovative ion-ion thrusters and steam rockets (Aanesland et al, 2014), and avoiding the need for neutralizers (Pelton, 2019). These developments are known to improve performance, reliability, and cost-efficiency of launch vehicles, enabling reduced weight, propellant consumption, and longer mission lifetimes (Holder et al, 2023). In addition, it is important to improve efficiency, safety, and environmental effect on propulsion systems, while reducing carbon footprint. Overall, these advances are known to redefine space transport, making it more sustainable, cost-effective, and efficient for future projects.

In rocket propulsion systems, some of the key innovations are modern materials, contour geometry, and high-energy propellants (Ortelt et al, 2017). There are significant impacts of these innovations on space missions by minimizing carbon footprint, specific impulse, and improved performance. Furthermore, advances in manufacturing are redefining production of hardware, resulting in reduced manufacturing times and costs for components (Cohn, 2012). Together, these innovative techniques result in development of sustainable, effective rocket engines to advance in expander cycle, orbital propulsion, and traditional gas generator engines (Joyner et al, 2008). These innovations are integrated into rocket propulsion to achieve improved dependence, thrust-weight

ratio, and minimized launch costs to improve capabilities of space exploration (Betts et al, 2011).

Novel thrust chamber geometries, ceramic matrix composites (CMC) for cooled chambers, magnetic propulsion and levitation, and 3D printing for complex components of engines are some of the key innovations in rocket propulsion systems. These innovations are beneficial with lower stage weight, enhanced impulse, possible reductions in cost, and avoiding loss of pressure from cooling. 3D printing has emerged as a promising technique of additive manufacturing to reduce lead times and costs (Yen-Sen, 2021). Table 3 lists recent innovations and their effects.

Table 3 Major Innovations for Space Missions

Recent Innovations	References
Taking care of astronauts' nutrition in space missions. Technologies developed to keep food safe for longer durations	Pandith et al (2023)
Recent advances in launch vehicles by focusing on electric pump for small vehicles	Jeong et al (2016)
Discussing technical difficulties in hybrid engines for space explorations along with solutions.	Glaser et al (2023)
Reducing manufacturing costs and enhancing payload benefits in AMBR engine. Technologies developed are prepared to fight and show benefits for missions.	Dankanich et al (2010)
Future space missions could be done with magnetic levitation of space satellites. VML emerged as a cost-effective alternative to existing systems	Sharma et al (2009)
Focusing on challenges like cryogenic engines and powerful electric propulsion. Key areas are propulsion, industry potential and deep space exploration	Freeman (2014)
Methane engines to be developed with global shifts. Methane or oxygen emerged as top propellant for space exploration	Jeong et al (2017)

In addition, advanced design methods and thrust chambers are promising technologies to improve engine reliability, cost-efficiency, and engine efficiency, making top-performing engines for both private and government transportation for space exploration (Ortelt et al, 2017). In thrust chamber and injector devices, additive manufacturing is incorporated for more complex geometries and efficient operation to improve overall performance of rocket engine (Beck et al, 2020). Finally, magnetic propulsion and levitation systems are proposed as more sustainable alternative for future vehicles to ensure reduced costs and proper thrust (West et al, 2016).

Especially with additive manufacturing, advances in rocket design have affected the cost-efficiency of missions (Buettner et al, 2023). Space tech giants like Blue Origin, SpaceX, Relativity Space, and Rocket Lab are using additive manufacturing for producing rocket engine, improving lead time and cost benefits. In addition, advances in cool thrust chambers are promising to improve specific engine life and impulse with ceramic matrix composites (Zhang et al, 2019). There are also novel techniques like "Laser Kinetic Energy Transfer (LKET)" systems providing cost-effective and simple approach to improve thrust and energy efficiency to redefine rocket propulsion (Ortelt et al, 2017). Along with mission performance, these advances are also promising to improve overall viability of endeavors related to space exploration.

VI. CONCLUSION

Additive manufacturing technologies have been adopted in rocket engine technology for valve housing, developing air-breathing thrusters, and advances in cooled chambers made of ceramic composites, and transpiration cooled chambers made of ceramic composites to reduce cost and improve efficiency. Because of reduced cost, efficiency, and sustainability, moving towards methane engines is a significant move for long-range plans related to space exploration. In addition, innovative designs of rocket engine are being explored on the basis of mathematical particle and space models, bringing new classifications of possible advances and rocket engines in energy efficiency. Together, these trends can redefine space missions in future by minimizing costs, improving performance, and achieving new technologies.

To conclude, recent advances in rocket propulsion system brought a breakthrough to use and explore space. With the appearance of electric rocket systems to refining the pursuit of reusable technologies and conventional chemical engines, these advances have both enhanced reliability and efficiency of space missions while opening new avenues for commercial missions, exploration and scientific studies. These propulsion systems are widely applied in several endeavors, i.e., from deployment of satellites and exploring deep space.

Each innovation takes scientific discovery closer to ambitious goals like manned Mars missions, commercialization of space, and sustainable habitats. In addition, these advances can redefine industries on Earth, i.e., from telecom to extraction of resources. When pushing the space exploration, there is a need to develop rocket propulsion systems and conduct further research. There are persistent challenges like reducing carbon footprint, minimizing cost, and improving efficiency. However, these challenges can be addressed while unlocking full potential of those technologies with collaboration among industry professionals, academicians, and government to usher in the new age for benefit of mankind and space exploration.

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