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Review on Past, Present and Future Rocket Propulsion Technologies

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Abstract

This paper offers a comprehensive exploration of the past, present, and future of rocket propulsion technologies. It begins by tracing the evolution of propulsion systems from their early innovations to the sophisticated systems that have propelled modern aerospace advancements. Through an in-depth review of historical propulsion systems, their design principles, and operational challenges, the paper illuminates the foundational technologies that have shaped contemporary rocket propulsion. This historical perspective provides valuable insights into the ingenuity and persistence of early rocket scientists, highlighting lessons that could inform future innovations. The technologies used in the present era of rocket propulsion are traced and discussed. Building on this foundation, the paper delves into emerging technologies and concepts poised to revolutionize space travel. These include the novelty in the use of atmospheric gas as reaction mass to address the mass problem in traditional propulsion, advancements in green oxidizers like nitroform and FOX-7 to reduce environmental impact, and the ambitious concept of antimatter annihilation rocket engines. The potential for faster-than-light travel through warp drives based on quantum field theory is explored, alongside the challenges and potentials of Nuclear Thermal Propulsion (NTP) systems, gel propellants, and pulse laser propulsion. The paper also addresses the formidable challenge of gravity-controlled propulsion, aiming to provide a holistic view of the technological landscape that could drive the next era of space exploration.

Introduction

This paper provides a thorough exploration of rocket propulsion technology, covering its historical evolution, current advancements, and future prospects. It begins by tracing the contributions of pioneers like Robert H. Goddard and Hermann Oberth and discusses the potential developments possible in the future while observing the existing technologies. The historical perspective underscores the progression from very fundamental propulsion systems to the sophisticated technologies that have driven space exploration from the Sputnik era to lunar missions and beyond.

Shifting to modern advancements, the paper examines how traditional propulsion methods face challenges in efficiency, payload capacity, and environmental impact. Emerging technologies, such as nuclear thermal rockets, antimatter-catalyzed fusion, and beamed energy propulsion, are discussed for their potential to revolutionize space travel and enable interstellar journeys. The paper also explores innovative ideas like using atmospheric gas as reaction mass, green oxidizers to reduce environmental impact, and the theoretical possibility of warp drives for faster-than-light travel.

By reviewing past achievements and current research, this paper highlights the lessons learned and the promising technologies that could shape the future of space exploration, offering insights into how humanity might continue its journey into the cosmos.

LITERATURE REVIEW

Morgan (et.al, 1985), in his paper from NASA, talks of the innovative concept of antimatter annihilation rocket engines and he explores the storage, extraction, and utilization of antimatter for propulsion in spacecraft. The paper describes how the energy is converted from the annihilation of protons and antiprotons into kinetic energy of charged ions, which is then transferred into a gas to produce thrust for the rocket. Using elements of higher atomic number for annihilation can amplify the energy output, which can help in increasing the thrust for potential interplanetary or even interstellar travel. The paper talks about the challenges of storing antimatter since it has a risk of annihilation and also proposes solutions for it such as electromagnetic fields and active refrigeration. The importance of controlled annihilation processes for efficient rocket thrust generation is emphasised throughout the document.[1]

Alcubierie (1994), in his paper, discusses the possibility of faster-than-light travel using a warp drive using spacetime distortion. The paper claims that to overcome the energy condition violations in achieving such travel, exotic matter is necessary. This conclusion is based on the principles of quantum field theory which allows negative field densities in specified scenarios. Plus, the paper also talks about the construction of spacetimes with closed causal curves using similar theoretical frameworks. The potential for faster-than-light travel while adhering to the fundamental principles of physics, by the local spacetime distortions to propel spaceships at significant speeds is a fascinating idea yet to be realized in the coming future.[2]

Roger A. (et.al. 1993) presented a conceptual study of a two-stage-to-orbit system, including a rocket and airbreathing engines. The study includes calculations of vehicle aerodynamics, performance, and weights. The minimum gross weight is attained by only using airbreathing engines; however, the empty weight is substantial. By incorporating rockets within the booster, the overall weight is reduced, the time required for staging is reduced, and the distance covered during cruise-back is decreased. Airbreathing engines have a high specific impulse but a low thrust-to-weight ratio, while rockets demonstrate a low specific impulse but a high thrust-to-weight ratio. The input also references prior research on the integration of airbreathing and rocket propulsion systems in launch vehicles, as well as the advantages and difficulties associated with this combination. The research determines that the inclusion of rockets decreases the weight of the vehicle when it is not carrying any payload, as well as the duration of the flight. Additionally, it lowers the distance the vehicle travels horizontally and the amount of fuel needed for the booster. [3]

Russell Daines (et.al, 1998) This analysis focuses on rocket-airbreathing combined-cycle propulsion systems (RBCC) as they pertain to applications from Earth to orbit. These engines generate a specific impulse averaged throughout the mission by integrating rocket and airbreathing components. The challenges encompassed in this domain are as follows: vehicle integration, multimode flow route design, fuel selection, blending and afterburning enhancement, and thermal choking mitigation. The potential of RBCC engines for Earth-to-orbit missions is attributed to their increased thrust and decreased oxygen consumption. The crucial considerations include engine and vehicle selection, flow path design, fuel selection, combustion sustainability, and the incorporation of supplementary subsystems.[4]

William J.D. Escher (et.al, 1999) This section discusses the notion of airbreathing/rocket combined-cycle (RBCC) propulsion as a means of powering future aircraft transportation. The text clarifies that RBCC propulsion systems may be classified into two categories: combination propulsion systems and combined-cycle systems. Combinedcycle systems are a group of highly interconnected engine types that merge airbreathing and rocket components. The input discusses many RBCC engine advancements, such as the RENE, Cryojet, LACE, Ejector Ramjet, and NASP. Additionally, it provides information on ongoing and future RBCC initiatives, including the NASA A STPART RBCC project, as well as the Hyper-X and Trailblazer flight tests. The discussion closes by examining the possible possibilities of RBCC propulsion for future aircraft transportation systems.[5]

C. R. McClititon (et.al, 1999) This article discussed the notion of airbreathing/rocket combined-cycle (RBCC) propulsion, which refers to a propulsion system that integrates airbreathing engines with rocket engines. The input states that there have been notable progressions in the field of hypersonic airbreathing vehicle technology and that some aspects of this technology are being confirmed via the use of flight experiments. The report also addresses the current state of hypersonic technological advancement in the United States. It proposes a strategic plan for the development of hypersonic technologies that are projected to be operational by the 2020s. The contribution highlights the significance of the evaluation of systems and conceptual designs, together with the choice of engine and structural ideas for hypersonic vehicles. The text also addresses the advancement of hypersonic propulsion, aerothermodynamics, and the design of materials and structural architecture. The contribution closes by addressing the Hyper-X program, which seeks to verify the feasibility of airframeintegrated, dual-mode scramjet-powered vehicles via flight testing. It also briefly mentions other current initiatives related to the development of hypersonic vehicles.[6]

William J.D. Escher (et.al, 2002) The paper explores the idea of "Spaceliners," which are reusable orbital transport platforms that use airbreathing propulsion. These devices are considered feasible alternatives to airplanes for delivering humans to space. The contribution proposes the development of a thorough collection of system evaluations by generating supplementary descriptions of potential system options. The primary design considerations for these systems include expendability/reusability, staging configurations, propellant selections, and takeoff/landing methods. The selection of the propulsion system, whether it be a rocket, airbreathing, or a hybrid of both, is also of utmost importance. Currently, there is a deficiency in having a universally accepted standard set of system idea descriptions that include all logical possibilities.[7]

A. Matesanz (et.al, 2002) the article focused on the examination of air-ejector rocket systems used in space propulsion. The main emphasis is on the computational fluid dynamics (CFD) method used to model the behavior of these systems, as well as the validation of the technique via actual experiments. The contribution also discusses the optimization of ejector nozzles to reduce thrust losses and enhance mission effectiveness. The text explores the difficulties in modeling and simulating the turbulent mixing layer in ejector rockets. It emphasizes the need to predict flow characteristics to effectively design these systems accurately. The contribution finishes by emphasizing the disparities between the measured and simulated outcomes in the numerical reconstruction of the experimental tests and the need for further enhancement in the physical models used in aeronautical vehicle system analysis.[8]

William J.D. Escher (et.al, 2003) the contribution explored the possible advantages of integrating airbreathing and rocket propulsion technologies in aeronautical transportation. By combining the advantages of airbreathing systems, such as their performance and operational flexibility, with the crucial in-space capabilities of rockets, it is proposed that future space transportation fleets may attain flight safety, reliability, and cost goals similar to those of airlines. The input differentiates between combination propulsion systems, which involve the installation of distinct engine types in the vehicle, and combined-cycle engines, which include interactive subsystems. An example of the Ejector Scramjet combined-cycle engine is provided. The input suggests that by combining airbreathing and rocket propulsion systems, it may be possible to achieve high levels of flight safety, mission reliability, and overall cost in future reusable-vehicle spaceflight advancements similar to those seen in airplanes.[9]

Stephen E. Stasko (et.al, 2004) this study covered the need for cost-effective and high-performance means of reaching space and suggested the use of tethers as a viable substitute for existing launch technologies. The concept entails the rendezvous of a suborbital launch vehicle with an orbiting tether, enabling the use of smaller and more cost-effective launch vehicles. Subsequently, the cargo is transported upwards along the tether by a lift vehicle and finally released at a certain height. This technology provides substantial cost reductions and consistent flight rates. The contribution also discusses the idea of a space elevator, which might ultimately replace the use of rockets, but recognizes the difficulties involved in making it a reality. An Earth-orbiting cable is considered a more practical and economical alternative. Additional research is required to enhance the modeling and analysis of the system's dynamics, as well as to tackle concerns like collision avoidance and the impact of the space environment.[10]

Casiano (et. al,2010) The operability advantage of liquid-propellant rocket engines (LREs)—thrust modulation or on-command variable thrust—has been the subject of infrequent research since the late 1930s. Throttleable rocket engines are capable of continuously altering trajectories to achieve the most economic flight, enabling optimum performance when compared to discrete throttling changes. The major methods of throttling LREs are High-Pressure-Drop Injectors, Dual-Manifold Injector, Gas Injection, Multiple Chambers, Pulse Modulation, Throat Throttling, Variable Area Injection, and Hydrodynamically Dissipative Injector.[11]

Johnson et al. (2011) Solar sail propulsion utilizes the solar radiation pressure exerted by the momentum transfer of reflected photons to generate a net force on a spacecraft. This method requires a large sail area to generate an appreciable momentum transfer, as the integrated effect of a large number of photons is necessary. Solar sails can be used for small satellite propulsion, which can be mass-efficient and reduce the need for dedicated chemical propulsion systems. It can also be utilized to deorbit small satellites at the end of their mission, meeting disposal requirements without additional propulsion systems. However, a large sail area is required to generate sufficient thrust, which can be a design and deployment challenge. And, due to the small size of some solar sail missions like NanoSail-D, it is often impossible to place much diagnostic instrumentation on board, necessitating reliance on ground imaging to confirm deployment and attitude.[12]

Herbertz et al. (2012) Ceramic thrusters are expected to be utilized in future rocket propulsion technologies due to their potential benefits, such as reduced weight, lower manufacturing costs, increased reliability, and higher lifetime due to thermal cycle stability. However, one disadvantage of ceramic thrusters is that they may not be the best option for small pressure-fed in-space propulsion applications, as radiation-cooled ceramic thrust chambers may be more suitable in such cases.[6] Wolański (2013) Detonative propulsion is considered a viable candidate for future rocket propulsion systems. The concept is attractive due to its potential for significant improvements in engine efficiency and simplification of engine design. Research has shown that propulsion efficiency could be improved with systems like Pulsed Detonation Engines (PDE) and Rotating Detonation Engines (RDE). There are significant technical challenges that have prevented the successful continuous operation of detonation propulsion systems. For example, the University of Michigan's attempts to develop a continuous detonation propulsion system did not achieve successful operation, and important questions remain unanswered. Additionally, research in some areas, such as laser detonation propulsion, has been limited to small demonstrators or theoretical analysis. [13]

Gabrielli and Herdrich (et.al, 2015), in their paper, provide a comprehensive overview of Nuclear Thermal Propulsion (NTP) systems and they highlight the long research tradition of NTP systems dating back to the late 1940s. They then discuss about the LOX Augmented Nuclear Thermal Rocket (LANTR), a hybrid engine that uses liquid oxygen gasification to combust hot hydrogen from the reactor. The review then discusses the challenges of Nuclear Salt Water Rockets (NSWR), including the risk of radiotoxic fission products contaminating Earth's biosphere. The paper also discusses fusion propulsion systems, including tandem mirror configurations and the Tokamak design, which are considered for astronautic missions to Jupiter.[14]

Trache et al. (2017) The article provides a detailed examination of recent advancements in energetic materials, focusing on the synthesis, properties, and applications of compounds like nitroform, FOX-7, and their derivatives. It highlights the environmental issues associated with traditional oxidizers such as ammonium perchlorate (AP) and the need for green alternatives like ammonium dinitramide (ADN), hydrazinium nitroformate (HNF), and phase-stabilized ammonium nitrate (PSAN). The review discusses the synthesis, crystallization, and coating of these green oxidizers, aiming to enhance performance, reduce sensitivity, and lower production costs in solid rocket propulsion. Additionally, it explores the thermal decomposition of ammonium nitrate (AN) and methods to improve its reactivity, including the use of additives, catalysts, and co-crystallization with potassium dinitramide (KDN). The development of high energy dense oxidizers (HEDOs) like CL-20 and TNENCA is also covered, emphasizing their potential to replace AP and reduce environmental impact. The article concludes by addressing the challenges in optimizing these compounds for solid rocket propellants and the ongoing research to find effective green replacements.[15]

Yu et al. (2018) The paper provides a comprehensive examination of pulse laser propulsion (PLP) technology, highlighting its potential applications and the challenges it faces. PLP, which utilizes pulse lasers to generate thrust through plasma formation from target materials, offers significant advantages such as increased payload capacity and reduced launch costs. The technology has been explored for various uses, including microsatellites, space debris removal, surface cleaning, and environmental monitoring. The paper discusses the dynamic processes involved in PLP, such as droplet propulsion, material ablation, and plasma generation through mechanisms like Multi-photon Ionization and Avalanche Ionization. Experimental setups and results are detailed, showcasing the propulsion of solid and liquid microspheres and the optimization of propulsion efficiency using different geometric structures and confining layers. Despite its promise, PLP faces challenges in stability at high altitudes and long-term operation, necessitating further research and real-world trials to fully harness its capabilities. The study is well-supported by numerous references, underscoring the depth of research in laser propulsion technology.[16]

Salgado et al. (2018) The concept of propellantless propulsion involves using techniques such as aerocapture to achieve orbit capture without the need for traditional chemical propellants. This method is considered a good candidate for future missions due to its potential to reduce the reliance on propellants, leading to cost savings and increased efficiency in space travel. However, propellantless propulsion technologies are still under development and have lower Technology Readiness Levels (TRL) compared to traditional chemical propulsion systems, which may pose challenges in their implementation for current missions.[17]

Basu. S (et.al, 2020) The review discusses recent advancements in electric propulsion technologies for future space travel. A brief description of electric propulsion is provided. Different methods of EP are discussed and compared. Among the types, Ion Thrusters and Hall-Effect Thrusters provide the most amount of specific thrust and efficiency. [18]

]A Mahjub (et.al, 2020) This paper discusses the importance of solid rocket motors and their optimization techniques. Solid rocket motors have been used for their high reliability, cost-effectiveness, and simpler structure to manufacture. Some of the modern metaheuristic-based optimization techniques for SRMs have been discussed. The GA approach is deemed a better optimization technique than HO and is also the most researched. The authors of this study have made an effort to highlight the most popular algorithms, design goals, current trends, and major obstacles in SRM design optimization.[19]

Verma, J. et al. (2021) Cryogenic technology has been instrumental in proving liquid propellant rockets to be the most efficient. The first liquid propellant rocket engine was fired in 1926 by Robert Goddard, which used liquid oxygen and gasoline as oxidizer and fuel, respectively. In rocket science, liquid propellants are often divided into three categories: petroleum-based fuel, cryogenic fuel, and hypergolic fuel. Known as a clean-burning fuel, cryogenic propellant holds particular relevance in the field of rocket research. These gases are liquefied and kept at extremely low temperatures. Liquid hydrogen (LH2) and liquid oxygen (LOX) are the most prominent cryogenic propellant fuels and oxidizers stored at -253°C and -183°C, respectively. The manufacturing and efficiency of liquid rockets have been significantly improved by cryogenic technology. The problems associated with cryogenic engines are mostly related to tank pressurization issues, for which helium gas is used to solve them.[20]

Padwal et al. (2021) The paper provides a comprehensive review of the current state of research on gel propellants, focusing on various aspects such as atomization, combustion, and rheological characterization. It compares the efficiency of different atomizers for gel propellants, emphasizing the importance of droplet size and gas-liquid ratio. Theoretical and numerical analyses of atomization processes are discussed, including stability analyses of sheets and jets, and the impact of rheological properties on these processes. The study also delves into the ignition mechanisms of gel propellants, highlighting the effects of parameters like initial droplet diameter and boron particle loading. The combustion behavior of gel propellants, particularly in rocket engines, is examined, with a focus on metalized gels and their performance parameters. Additionally, the paper reviews mathematical models for the vaporization and combustion of gel droplets, noting the complexities involved in these processes. Experimental studies on the mixing behavior of impinging jets and the combustion of hypergolic and non-hypergolic gel droplets are also summarized. The paper concludes by identifying challenges in optimizing metal loading and stability in gel fuels, and calls for further research to advance the field of gel propellants for propulsion applications.[21]

Rosato et al. (2021) The paper investigates stabilized detonation waves for hypersonic propulsion through a combination of experimental and numerical simulations. The study focuses on three distinct reaction behaviors leading to different burning modes, utilizing the experimental facility HyperReact at the University of Central Florida. The results highlight the presence of stable oblique detonation waves at high pressures and temperatures, shedding light on the controllability of various burning modes in hypersonic reacting flows. The unique experimental configuration presented in the study demonstrates controlled detonation initiation and stabilization in a hypersonic flow, offering a promising pathway for developing ultra-high-speed detonation technology for advanced propulsion systems. Sponsored by the Air Force Office of Scientific Research and supported by NSF, the experimental and computational studies delve into the use of a 30-degree turning angle ramp to stabilize the detonation wave. High-speed schlieren and chemiluminescence imaging techniques were employed to capture the behavior of oblique detonation waves in hypersonic flow, providing valuable insights into this phenomenon. Overall, the paper's findings represent a significant breakthrough in high-speed propulsion technology with potential implications for future applications in the field.[22]

Srivastava. S (et.al, 2022) This review provides a comprehensive outlook over hybrid rocket engines over the years, including the major challenges that are faced by manufacturers and operators. The authors have highlighted the importance of choosing the right propellants in hybrid form to achieve optimal results. Computational advancements, like numerical simulations, are recommended to enhance the performance. [23]

Barato F. (et.al, 2023) This paper focuses on green propulsion achieved by hybrid rockets using specific oxidizer-fuel combinations. The issues related to rocket propulsion effluents in the atmosphere are briefly discussed. The possible use of alternative sustainable fuels that are carbon-neutral, or are not derived from fossil fuels is proposed, and some of them are listed. Of all, thermoplastic fuels, polyethylene, polypropylene, and paraffin wax are the best contenders in terms of propulsive characteristics, low costs, and large availability. [24]

Saboktakin. A (2023) The author emphasizes the use of piston pumps for pressurization of fuel and oxidizer in a liquid propellant engine. Piston pumps are said to have a lighter weight and competent efficiency as compared to other pump types. Important considerations before the design are listed. [25]

METHODOLOGY

PAST TECHNIQUE

Solid propulsion was the first propulsion type to be used in rockets. One of the first attempts was when Theodore Von Karman and his team experimented with and tested different types of gunpowder, asphalt and potassium perchlorate-powered rockets at the California Institute of Technology's GALCIT labs.[26]. Some problems associated with the solid propellant rocket motors include undesirable oscillatory combustion effects in longitudinal mode, tangential mode. The reasons for this could be propellant formulation, motor geometry and transient pressure perturbations.[27] With the development of advanced computing methods and tools, there have been aiding the production of bigger solid rocket motors. The modeling of the operation and the rocket of segmented solid rocket motors.[28] There are various methods to predict the performance, specific and total impulse before fabrication and test of the solid rocket motor.[29] There are various merits and demerits of hybrid engines compared with those of solid and liquid engines. They are shown to have a relatively lower risk of explosion in comparison to solid rocket motors and are simpler in structure and operation when compared to liquid rocket engines. The time and cost of developing a hybrid engine are significantly lower than those of a liquid engine. Liquid oxygen is the most sought-after oxidizer. The LOX-SBR (Styrene Butadiene Rubber) hybrid combination produces the highest amount of specific impulse, on par with solid and liquid engines.[30]

PRESENT TECHNIQUE

The RBCC engine, which combines ramjets with rocket engines, faces challenges in generating adequate thrust at low speeds. The two most common configurations of RBCCs at the moment are -

- The rectangular section
- The axisymmetric arrangement

Rocket-Based Combined Cycle (RBCC) engines are rectangular and axisymmetric, featuring back-forward step and strut-rocket topologies. They have eject rockets mounted in the center axis or around it and an axisymmetric flow route. Examples include the TSTO system and E3 engine (fig 2). These engines are typically positioned in lower aircraft areas and have integrated inlets and nozzles for compression and free-flow capture. Research on axisymmetric RBCC engines began in 1958 in the US. [31]

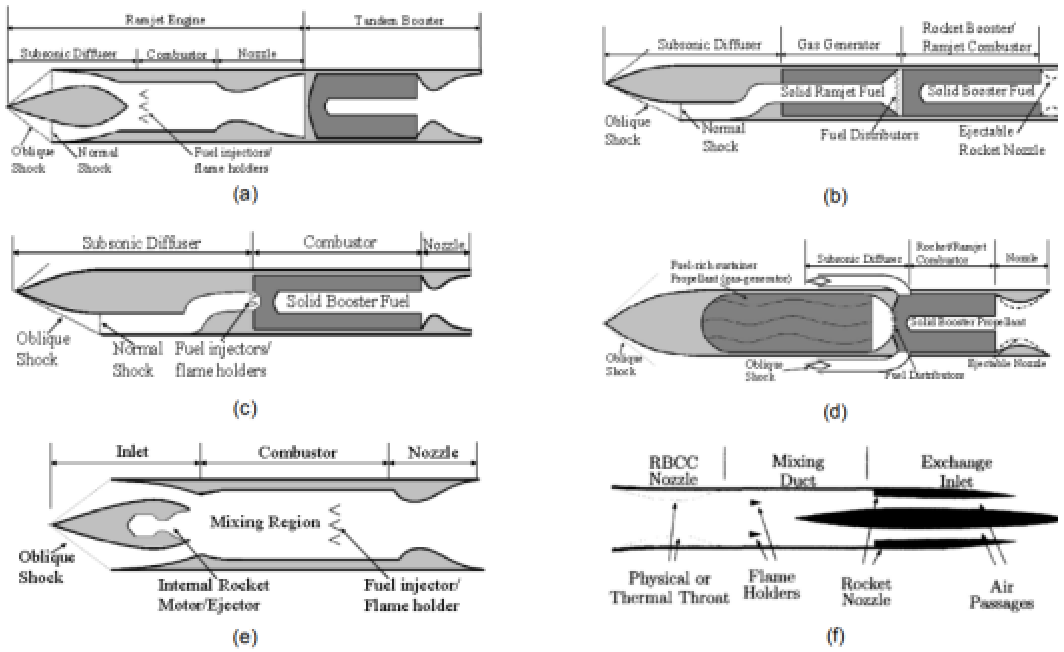

Figure-1[10] : (a) Tandem solid booster with a canister ramjet; (b) Solid fuel integral-rocket ramjet (IRR); (c) Liquid fuel IRR; (d) Air-ducted rocket; (e) Central ejector RBCC; (f) Annular ejector RBCC[32]

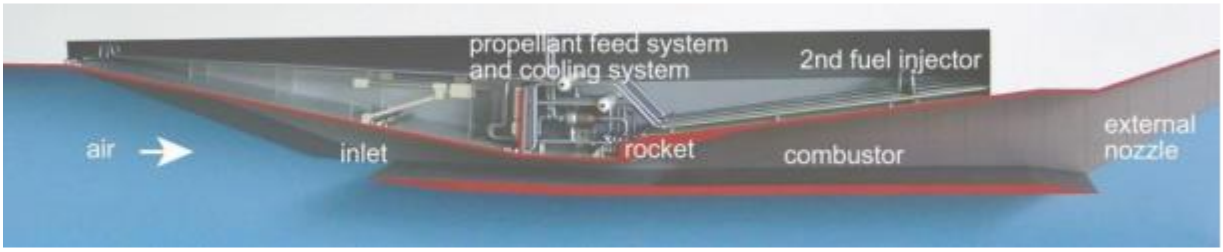

Figure 2: Japanese schematic for the E3 engine.[33]

Moreover, the integration of RBCC (Rocket-Based Combined Cycle) and TBCC (Turbojet-Based Combined Cycle) models is valuable for demonstrating the capabilities of liquid rocket engines, facilitating streamlined and optimal design and operation within a unified framework.[34] NASA utilizes the NPARC approach in CFD to evaluate the combined performance of rocket-based combined cycle (RBCC) engines, demonstrating its effectiveness in subscale tests. An analytical method using computational fluid dynamics (CFD) was created to improve the inlets in rocket-based combined cycle propulsion systems. Additionally, a technique for determining the system's internal drag was devised.[35] NASA Glenn Research Center is partnering with NASA to create a rocket-powered combined-cycle propulsion system utilizing the reusable Single-Stage-To-Orbit (SSTO) launch vehicle Trailblazer.[36] Hence, RBCC engines integrate rockets' high thrust-to-weight ratio with ramjets' high specific impulse, creating a single propulsion system. [37] The necessity for reusable launch vehicles (RLV) in order to save expenses. The RBCC engine, which combines rocket and air-breathing engines, is proposed as a feasible solution.[38] The cooperative evolutionary method is utilized to enhance the performance of RocketBased Combined-Cycle (RBCC) engines by eliminating individuals in specific situations, thereby enhancing their adaptability in various modes.[39] The rocket-based combined cycle (RBCC) engine can operate in ejector, ramjet, scramjet, or pure rocket mode. Due to their cost-effectiveness and reliability, RBCC engines are promising propulsion technologies for launching applications.[40] The Rocket-Based Combined-Cycle (RBCC) engine may cut payload launch costs. The rocketramjet combined-cycle engine in air-breathing scramjet flow paths can power launch vehicles. Japan Aerospace Exploration Agency (JAXA) has sought the best engine configuration and mode. The engine operates as an ejector-jet, ramjet, scramjet, and rocket. Missions require high specific impulse in the ramjet mode, and shock train systems can improve the engine for subsonic speed deceleration.[41] The RBCC operates in the ejector mode, which allows for a more efficient takeoff by combining the characteristics of air-breathing and rocket engines. It requires less energy than conventional rockets.[42]

FUTURE TECHNIQUE

Antimatter propulsion holds significant potential for future rocket propulsion systems. The concept involves utilizing the energy released from matter-antimatter annihilation, which results in a high conversion of their rest masses into kinetic energy of other massive particles, photons, and neutrinos. This process could provide a highly efficient source of thrust for space vehicles. The potential applications of antimatter propulsion include geocentric, interplanetary, and interstellar flights. For instance, it could be advantageous for missions involving LEO-GEO transfers for platforms and heavy telecommunications satellites, as well as lower-energy transfers for scientific satellites. Additionally, antimatter propulsion could enable extended missions, such as exploring the interstellar medium and observing the Solar System from distances greater than 100-200 AU. However, the development of antimatter propulsion faces formidable challenges, including the production, storage, extraction, and annihilation control of antimatter. Despite these challenges, the theoretical advantages suggest that antimatter propulsion could open new frontiers in space exploration and make several future space missions more feasible.[43]

Gel propellant could be a potential candidate for future rocket propulsion because it offers several advantages, such as increased energy density when metal particles are introduced into the gel matrix, which is higher compared to neat-liquid propellants. Additionally, gel propellants provide full pulse-width-modulation capabilities and the ability for divert and attitude control system applications, making them attractive for both tactical and space applications. However, There are several demerits or disadvantages associated with gel propellants. The non-Newtonian complex theological character of these propellants and the resulting system-level implications make their use in operational rocket engines very challenging . Furthermore, handling and testing of toxic and corrosive materials like Fig. 3[5]: The concept of solar sail propulsion hydrazine-based gel fuels require significant safety precautions, which complicates their practical application.[44]

Another mode of propulsion proposed is gravity-controlled propulsion. However, the practical benefits of gravity control would be limited only to space propulsion as it would bring only modest gains in terms of launching spacecraft and no breakthrough for propulsion in general. Additionally, altering the vacuum properties and the relative strength of known fundamental interactions of nature, which would be necessary for gravity control, are beyond current theoretical knowledge and foreseeable technological developments. These limitations make gravity control not a potential candidate for future rocket propulsion.[45]

CONCLUSION

This paper discusses all the notable developments in the past rocket propulsion technologies since the beginning of the space exploration era. The first solid rocket motors, liquid propellant rocket engines, hybrid rocket engines, their advancements, merits and demerits, replacements are discussed. As we look to the future of space exploration, understanding the evolution of propulsion technologies reminds us of the importance of building upon past achievements to drive continued progress and discovery in the final frontier.

The future of rocket propulsion systems is poised at the brink of significant advancements, driven by a combination of technological innovation and growing interest in space exploration. Emerging propulsion technologies, such as ion propulsion, antimatter propulsion, and nuclear propulsion, are expected to revolutionize space travel by offering higher efficiency, longer lifespan, and greater speeds compared to traditional chemical rockets.

For instance, ion propulsion systems, which use electric power to ionize and accelerate propellant, offer exceptionally high specific impulse, making them ideal for longduration missions. Similarly, nuclear propulsion, harnessing the immense energy of nuclear reactions, holds promise for enabling faster and more efficient interplanetary travel.

Furthermore, advancements in materials science and engineering are paving the way for the development of reusable rockets, which could significantly reduce the cost of space travel. However, these technologies also present new challenges, including technical complexities, safety concerns, and regulatory issues, which must be addressed to realize their full potential. As such, the future of rocket propulsion will likely be shaped by a dynamic interplay of technological, economic, and regulatory factors.

REFERENCES

1. D. L. Morgan Jr., "CONCEPTS FOR THE DESIGN OF AN ANTIMATTER ANNIHILATION ROCKET," 1985.
2. M. Alcubierre, "The Warp Drive: Hyper-fast Travel Within General Relativity," Classical and Quantum Gravity, vol. 11, no. 5, pp. L73–L77, May 1994.
3. R. A. Lepsch and C. J. Naftel, "Winged booster performance with combined rocket and airbreathing propulsion," J. Spacecr. Rockets, vol. 30, no. 6, pp. 641–646, 1993.
4. R. Daines and C. Segal, "Combined rocket and airbreathing propulsion systems for space-launch applications," J. Propuls. Power, vol. 14, no. 5, pp. 605–612, 1998.
5. ,W. J. D. Escher, "a U.S. History of Airbreathing/Rocket Combined-Cycle (Rbcc) Propulsion for Powering Future Aerospace Transports, With a Look Ahead To the Year 2020," Aiaa, p. 23, 1999.
6. T. V. Vehicles and I. Ricketts, "November 14,1999/Norfolk, VA '," no. c, 1999.
7. W. J. D. Escher, "Initial characterization of airbreathing-capable non-staged earth-to-orbit transportation systems," 38th AIAA/ASME/SAE/ASEE Jt. Propuls. Conf. Exhib., no. July, pp. 1–11, 2002
8. A. Matesanz, A. Velazquez, J. Tizon, and J. Montanes, "Numerical reconstruction of ejector rocket experimental tests," J. Propuls. Power, vol. 18, no. 6, pp. 1191–1198, 2002.
9. W. J. D. Escher, "AIAA 2003-5266 On the Airbreathing / Rocket Propulsion Relationship : For Advanced Spaceflight Systems , It ' s the Combination that Counts American Institute of Aeronautics and Astronautics," no. July, pp. 1–20, 2003.
10. S. Stasko and G. Flandro, "The Feasibility of an Earth Orbiting Tether Propulsion System," no. July, pp. 1–8, 2004.

11. Casiano, Matthew J., James R. Hulka, and Vigor Yang. "Liquid-propellant rocket engine throttling: A comprehensive review." Journal of propulsion and power 26.5 (2010): 897-923. [8]Umholtz, Philip. "The history of solid rocket propulsion and aerojet." 35th Joint Propulsion Conference and Exhibit. 1999.
12. L. Johnson, M. Whorton, A. Heaton, R. Pinson, G. Laue, and C. Adams, “NanoSail-D: A Solar Sail Demonstration Mission,” Acta Astronautica, vol. 68, no. 5–6, pp. 571–575, Mar. 2011.
13. Herbertz, M. Ortelt, I. Müller, and H. Hald, “Potential Applications of the Ceramic Thrust Chamber Technology for Future Transpiration Cooled Rocket Engines,” Transactions of the Japan Society for Aeronautical and Space Sciences, Aerospace Technology Japan, vol. 10
14. R. A. Gabrielli and G. Herdrich, “Review of Nuclear Thermal Propulsion Systems,” Progress in Aerospace Sciences/Progress in Aerospace Sciences, vol. 79, pp. 92–113, Nov. 2015.
15. D. Trache, T. M. Klapötke, L. Maiz, M. Abd-Elghany, and L. T. DeLuca, “Recent Advances in New Oxidizers for Solid Rocket Propulsion,” Green Chemistry, vol. 19, no. 20, pp. 4711–4736, Jan. 2017.
16. H. Yu, H. Li, Y. Wang, L. Cui, S. Liu, and J. Yang, “Brief Review on Pulse Laser Propulsion,” Optics & Laser Technology/Optics and Laser Technology, vol. 100, pp. 57–74, Mar. 2018.
17. M. C. V. Salgado, M. C. N. Belderrain, and T. C. Devezas, “Space Propulsion: A Survey Study About Current and Future Technologies,” Journal of Aerospace Technology and Management, vol. 10, Feb. 2018.
18. Basu, Sourav, et al. "An analytical review on electric Propulsion systems for space satellites." INCAS Bulletin 12.4 (2020): 3-11.
19. Mahjub, Ahmed, et al. "Design optimization of solid rocket propulsion: a survey of recent advancements." Journal of Spacecraft and Rockets 57.1 (2020): 3-11. [2]Barato, Francesco. "Review of Alternative Sustainable Fuels for Hybrid Rocket Propulsion." Aerospace 10.7 (2023): 643
20. Verma, J., A. P. Singh, and D. Sharma. "A comprehensive review of propellants used in cryogenic rocket engines." Vidyabharati Int. Interdiscip. Res. J 11.2 (2021): 8-17.
21. M. B. Padwal, B. Natan, and D. P. Mishra, “Gel Propellants,” Progress in Energy and Combustion Science, vol. 83, p. 100885, Mar. 2021
22. D. A. Rosato, M. Thornton, J. Sosa, C. Bachman, G. B. Goodwin, and K. A. Ahmed, “Stabilized Detonation for Hypersonic Propulsion,” Proceedings of the National Academy of Sciences of the United States of America, vol. 118, no. 20, May 2021
23. Srivastava, Sachin, and Amit Kumar Thakur. "Review on hybrid rocket engine: past, present and future scenario." International Journal of Vehicle Structures & Systems 14.5 (2022): 680-685
24. Barato, Francesco. "Review of Alternative Sustainable Fuels for Hybrid Rocket Propulsion." Aerospace 10.7 (2023): 643
25. Saboktakin, Abbasali. "A comprehensive review on reciprocating pumps for space rocket systems." Journal of Power Technologies 103.1 (2023).
26. Umholtz, Philip. "The history of solid rocket propulsion and aerojet." 35th Joint Propulsion Conference and Exhibit. 1999.
27. Karnesky, A. L., and S. E. Colucci. "Recent occurrences of combustion instability in solid rocket motors-An overview." Journal of Spacecraft and Rockets 12.1 (1975): 33-38.
28. Davenas, A., and J. Thepenier. "Recent progress in the prediction and analysis of the operation of solid rocket motors." Acta astronautica 44.7-12 (1999): 461-469.
29. George, D. "Recent advances in solid rocket motor performance prediction capability." 19th Aerospace Sciences Meeting. 1981.
30. Mukunda, H. S., V. K. Jain, and P. J. Paul. "A review of hybrid rockets: Present status and future potential." Proceedings of the Indian Academy of Sciences Section C: Engineering Sciences 2 (1979): 215-242

31. T. tian Zhang, Z. guo Wang, W. Huang, J. Chen, and M. bo Sun, "The overall layout of rocket-based combined-cycle engines: a review," J. Zhejiang Univ. Sci. A, vol. 20, no. 3, pp. 163–183, 2019, doi: 10.1631/jzus.A1800684.
32. D. E. Wood, "Investigations of an innovative combined cycle nozzle," p. 112, 2009,
33. T. Kanda, S. Tomioka, S. Ueda, K. Tani, and Y. Wakamatsu, "Design of sub-scale rocket-ramjet combined cycle engine model," Int. Astronaut. Fed. - 56th Int. Astronaut. Congr. 2005, vol. 7, pp. 4599–4611, 2005
34. T. Lavelle, "The Computing & Interdisciplinary Systems Office," pp. 101–113, 2003.
35. J. R. DeBonis and S. Yungster, "Rocket-based combined cycle engine technology development - Inlet CFD validation and application," NASA Tech. Memo., no. 107274, pp. 1–8, 1996.
36. S. Yungster and C. J. Trefny, "AIAA 99-2393 Analysis of a New Rocket-Based Combined-Cycle Engine Concept at Low Speed Institute for Computational Mechanics in Propulsion 35th AIAA / ASME / SAE / ASEE Joint Propulsion Conference and Exhibit," no. June, 1999.
37. H. D. Perkins, S. R. Thomas, and J. R. DeBonis, "Rocket-based combined cycle propulsion system testing," J. Propuls. Power, vol. 14, no. 6, pp. 1065–1067, 1998.
38. M. Kodera, H. Ogawa, S. Tomioka, and S. Ueda, "Multi-objective design and trajectory optimization of space transport systems with RBCC propulsion via evolutionary algorithms and pseudospectral methods," 52nd Aerosp. Sci. Meet., no. January, pp. 1–14, 2014
39. D. Pastrone and M. R. Sentinella, "for RBCC Engines Optimization," no. July, pp. 1–13, 2008.
40. B. Bin Lin, H. L. Pan, F. Qin, G. Q. He, X. G. Wei, and L. Shi, "Effects of Fuel-Lean primary rocket on bypass ratio in RBCC ejector mode," 50th AIAA/ASME/SAE/ASEE Jt. Propuls. Conf. 2014, pp. 1–8, 2014
41. T. Kouchi, K. Kobayashi, K. Kudo, A. Murakami, K. Kato, and S. Tomioka, "Performance of a RBCC combustor operating in ramjet mode," Collect. Tech. Pap. - AIAA/ASME/SAE/ASEE 42nd Jt. Propuls. Conf., vol. 7, no. July, pp. 5325–5338, 2006,
42. Y. Yao et al., "Thrust performance of the rocket-based combined-cycle engine under ejector mode," AIP Adv., vol. 13, no. 8, 2023.
43. G. Vulpetti, "Antimatter Propulsion for Space Exploration," Journal O F the British Interplanetary Society, vol. 39, p. 391, Sep. 1986.
44. S. Rahimi, A. Peretz, and B. Natan, "Rheological Matching of Gel Propellants," Journal of Propulsion and Power, vol. 26, no. 2, pp. 376–379, Mar. 2010.
45. O. Bertolami and M. Tajmar, "Hypothetical Gravity Control and Implications for Spacecraft Propulsion," arXiv (Cornell University), Jan. 2002.