IJHSR
ijhighschoolresearch.org
REVIEW ARTICLE

Practicality Analysis of Air-Breathing Launch Vehicles

Geunhyung Hong

Seoul International School, 15-Seongnam-daero, 1518beon-gil, Seongnam-Si, Gyeonggi-do, 13113, South Korea; lucas.gh.hong@gmail.com

ABSTRACT: Reusable rocket technology is crucial for reducing launch costs and enabling long-term space missions. Traditional rockets carry both fuel and oxidizer, which adds mass and limits efficiency. Air-breathing rocket engines offer a solution by drawing oxygen from the atmosphere during ascent, similar to jet engines, reducing the need for onboard oxidizers. Key designs, such as SABRE and RBCC, explore this concept. While air-breathing engines enhance efficiency and specific impulse, traditional rockets offer advantages in structural simplicity and lower empty mass fractions.

KEYWORDS: Physics and Astronomy, Mechanics, Aerospace, Propulsion, RBCC Engine.

Introduction

The ability to launch into Earth's orbit has allowed for significant developments in both civilian and military fields. Satellites provide unprecedented coverage for real-time data, while manned space launch vehicles continue to lead breakthroughs in space exploration. Since the early days of rocket development, namely the 1950s, space agencies have constantly been searching for alternate means of travel into orbit that are of higher reliability, lower cost, and can be carried out more regularly. Early proposed solutions to this problem came in the form of traditional launch systems that have been modified to be reusable, which would ideally be able to launch on short notice and incur much lower rates of cost-per-launch. The Space Shuttle, proposed in the 1970s by NASA, and shown in Figure 1, was one of the first launch vehicles of this type. Completely reusable by design, the space shuttle was designed to reduce the launch costs of satellites into orbit. The reusable system would allow for much more frequent launches with short turnaround times between launches of the same vehicle.[1]

However, the space shuttle fell way short of its goals, its highest-ever launch rate being a mere 11 launches per year. Design flaws in cost optimization resulted in significantly longer turnaround times for the launch vehicle than expected, and later launch costs sat at over $10,000 per pound of payload.[1] For the sake of future satellite launches and long-term manned missions to space, a clear need exists for a responsive launch vehicle capable of easy space access, and recent research suggests that hypersonic air-breathing propulsion may hold the key.

Air-breathing propulsion has developed unprecedentedly over the past decades, and it has become widely accepted that it is either presently or potentially a competitor of the traditional rocket engine for almost every propulsion task.[2] Compared to the rocket engine, hyper-velocity air-breathing devices offer a much higher thrust coefficient and drastically improved fuel-specific impulse.[2] Specific impulse is defined as thrust output per unit propellant flow rate. Traditional rockets require fuel and oxidizer as part of their propellant. However, air-breathing systems can acquire oxygen from the surrounding atmosphere, eliminating the oxidizer component entirely (atmospheric oxygen is not counted as an onboard propellant).[1] As Figure 1 clearly outlines, while typical rockets have a specific impulse of around 500 seconds, air-breathing systems can reach values of over 7000 seconds without much difficulty. A higher specific impulse correlates with higher fuel efficiency; given the same propellant mass, an air-breathing engine produces more thrust than a rocket.[1] It is also worth noting that by the very nature of their design, air-breathing propulsion methods are more reliable than rocket-based ones. Air-breathing engines operate at comparatively lower chamber pressures, providing longer service life and safety. Air-breathing engines are also much less prone to catastrophic failures than rockets, giving the onboard crew more time to escape in the event of disaster.[1]

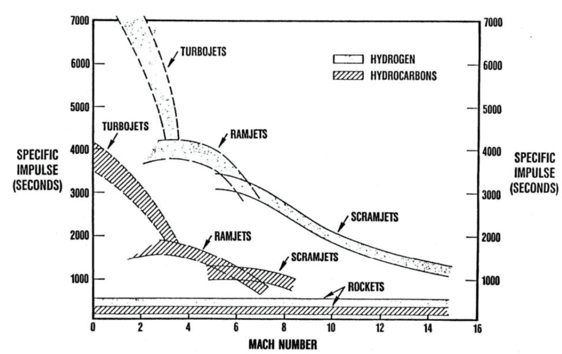

Figure 1: Specific impulse versus Mach number for various propulsion types. The figure illustrates how air-breathing engines significantly outperform conventional rocket engines in terms of specific impulse, especially at higher Mach speeds. This result demonstrates the superior fuel efficiency of aerothermal propulsion systems. These trends indicate the potential of air-breathing technologies to optimize performance in hypersonic regimes.[1]

However, there are also a handful of areas in which the traditional rocket engine offers the upper hand. A rocket engine is much simpler in design, which brings the advantages of lower zero fuel weight and ease of maintenance.[2] Moreover, it applies under almost any atmospheric condition and can operate over various speeds. On the other hand, air-breathing engines have limited operability in high-altitude conditions and are generally insufficient to take a launch vehicle into orbit. More-

DOI: 10.36838/v8i1.106

over, each type of air-breathing engine has a specified speed range in which it can operate efficiently, and implementation would require a hybrid propulsion system capable of transitioning seamlessly between respective propulsion systems.[1] Air-breathing engines offer advantages in gross mass and specific impulse, but their technical complexity leads to a higher vehicle empty mass (mass with fuel excluded) than their rocket counterparts.[1] They are also less aerodynamically efficient, as the airframe must conform to a shape that leaves room for a compressor and nozzle.

While air-breathing propulsion offers advantages in efficiency, the benefits are offset by penalties for the vehicle's empty mass and deficiencies in aerodynamics. In this essay, air-breathing launch vehicles will be compared with conventional rockets based on efficiency, which will be determined through comparisons of the vehicle's specific impulse and dry weight. HySIDE modeling will be referenced to help model the characteristics and performance of the respective vehicles.

History of Hybrid Air-Breathing Engines

SR-71 Blackbird:

Conceived in the 1960s as an airborne reconnaissance platform, the SR-71 Blackbird (Figure 2) holds a unique title in aeronautics as the fastest-ever crewed air-breathing vehicle to take flight. With its powerful J-58 engines, the aircraft could attain a cruise speed of Mach 3.2 and an operational altitude of 90,000 ft.[3] 93 percent of the aircraft's total mass consisted of pure Titanium, and large sections of the leading and trailing edges, vertical stabilizers, and inlet spikes were crafted out of laminates of phenyl silane, silicone-asbestos, and fiberglass, which helped reduce the aircraft's radar footprint.

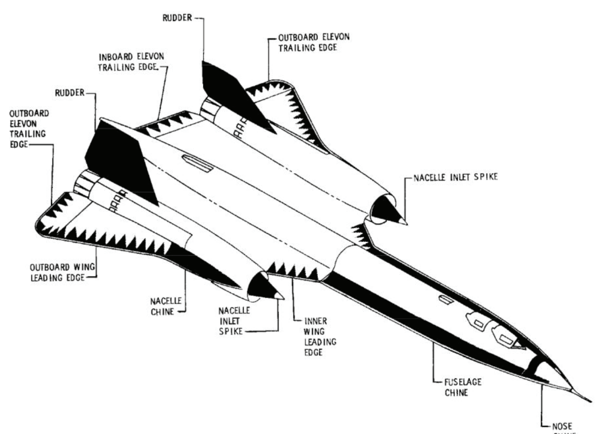

Figure 2: Wing and fuselage of the SR-71 Blackbird. Titanium-heavy design, along with radar-absorbing materials, enabled high-speed reconnaissance and stealth performance.[3]

The most unique feature of the SR-71 was its propulsion system. The two JT11D-20 (J58) afterburning engines installed on the aircraft were capable of transitioning between a low-mach-number and high-mach-number jet engine through a variable-geometry inlet diffuser and air-bleed bypass system that allowed inlet air to be fed directly into the afterburner at high speeds, effectively transforming the engine to a ramjet (Figure 2). During high-speed flight, the inlet and exhaust ejector generated over 80% of the total thrust output.[3-5] The hybrid design of the engine gave the SR-71 superb high-altitude performance and allowed it to cruise at hypersonic speeds with unmatched efficiency. A movable inlet spike located forward of the combustion chamber actively moderated airflow into the engine, along with forward bypass doors that opened and closed automatically as a function of pressure gauged by the ducts.

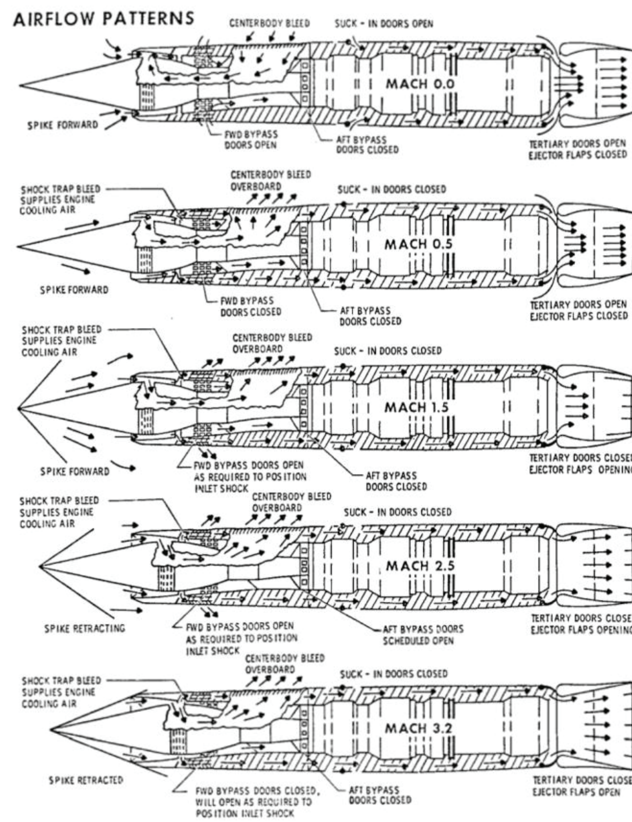

Figure 3: Operation of SR-71's J58 engines from zero to cruise Mach number. This diagram outlines the engine's transition from turbojet to ramjet-like functionality using a variable-geometry inlet and air-bypass system, enabling efficient hypersonic cruise. This adaptive propulsion mechanism allowed the aircraft to seamlessly operate across a wide range of velocities.[4,5]

Synergetic Air-Breathing Rocket Engine (SABRE):

The SABRE is the first engine design for space launch vehicles that uses environmental oxygen as an oxidizer in its combustion chamber. Derived from the precooler concept, the SABRE effectively functions in 2 rocket modes: a primary propulsion system that uses an air-breathing engine and a secondary mode consisting of a traditional rocket engine to propel the vehicle into orbit in SSTO mode.[6-8] Unlike the J-58 engine installed on the SR-71, the SABRE is a hybrid of air-breathing and oxidizer-fed propulsion systems. It promises cost-effective, reliable, responsive space launches with dramatically increased payload size. It also allows space launch vehicles to enter a stable cruise within the Earth's atmosphere at hypersonic speeds(Approximately Mach 5.5), something traditional rocket engines are not capable of doing.[6-8]

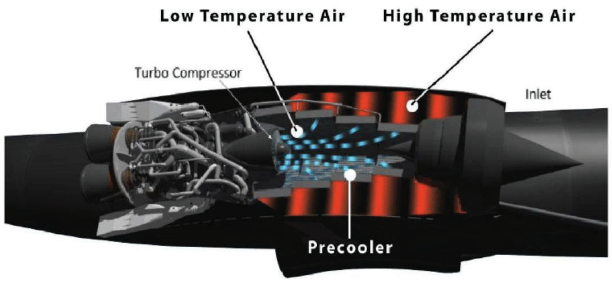

Figure 4: Schematic of the SABRE engine. The diagram illustrates the hybrid operation of the SABRE engine. This system shows when atmospheric air is cooled in a precooler before compression and combustion, and transitions to rocket mode as altitude increases. This dual-mode functionality supports both atmospheric and orbital flight within a single-engine framework.[6-8]

As illustrated in Figure 4 above, atmospheric air entering the engine is initially slowed down by the inlet spike. It flows along the outer fringes of the chamber before flowing inwards through the precooler mechanism and entering the compressor in a low-temperature state.

Rocket-Based Combined Cycle propulsion system (RBCC):

Similar to the SABRE engine, the Rocket-Based Combined Cycle (RBCC) bridges performance gaps between rockets and air-breathing engines. During the static to transonic flight regime, the engine behaves similarly to a traditional turbojet engine before transitioning to a ramjet/scramjet engine in mid to high-speed flight. Once the vehicle reaches near orbital speeds, the engine can transition into a pure rocket while sharing the overall systematic structure.[5] Combined Cycle engines, including the RBCC, offer numerous advantages, including increased efficiency. While a conventional rocket is highly inefficient at low Mach numbers and altitudes, the RBCC's employment of air-breathing propulsion before reaching speeds beyond Mach 11 does away with the rocket burn during initial ascent, replacing it with a much more effective air-augmented propulsion system before the launch vehicle reaches the upper atmosphere.[9-11] The different operating stages of the RBCC engine are illustrated below in Figure 5.

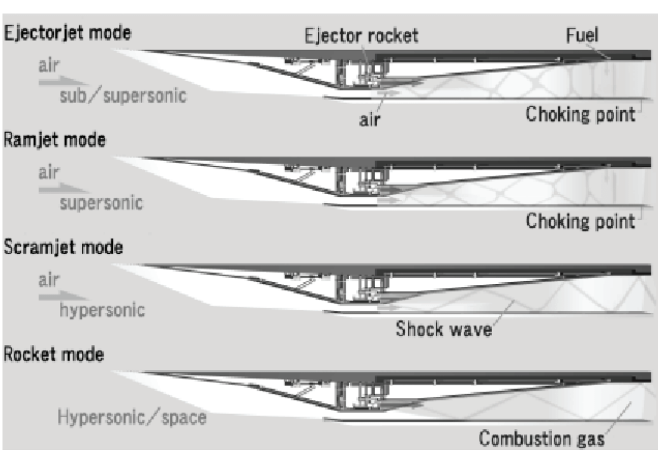

Figure 5: Operation modes of the Rocket-Based Combined Cycle (RBCC) engine. The figure visualizes the four main operating stages: ejector-ramjet, ramjet, scramjet, and rocket mode, depending on vehicle speed and altitude. Each transition enhances propulsion efficiency during different phases of the vehicle's ascent.[9-11]

Methodology

Introduction to Specific Impulse:

The specific impulse, usually abbreviated as Isp, defines the quantity of thrust produced when 1kg of propellant is consumed for 1 second, or more simply, how many seconds a propellant can accelerate its mass when operating under 1g. It is also the reciprocal of Specific Fuel Consumption (SFC).[12-14] In simple equation form, ISP can be expressed as:

$$I_{sp} = \frac{T}{\dot{m}_{propellant} \cdot g}$$

As previously mentioned, specific impulse is a parameter that must be considered when analyzing air-breathing and rocket-based propulsion systems, as it effectively quantifies the fuel efficiency of any engine. Many existing essays on this topic use specific impulses as the basis for comparison. Whitlow explored NASA Glenn RBCC and TBCC concepts and analyzed propulsion performance using a specific impulse.[7] S. Orloff used specific impulse, specific fuel consumption, and dry vehicle weight to compare airbreathing propulsion systems to rocket propulsion in SSTO systems.[1] Lindley explored specific impulse parameters across different operating conditions, along with thrust coefficient values in the analysis of RBCC vehicles.[2]

Calculation of Specific Impulse:

While the equation above explains a specific impulse(Isp), using it as a measure of propulsion performance warrants more detailed analysis. The effective specific impulse(Ieff) is defined as the sum of all forces in the direction of motion, considering propulsion, gravity, and aerodynamic effects, divided by the propellant flow rate.[7] Ieff can vary significantly throughout different phases of flight as the parameters above change. Making it inadequate for use in PFR(Propellant Fraction Required) calculations. Thus, a constant, equivalent value of Ieff may be used instead, defined as I*. The rocket equation for PFR is given as $PFR=1-e^{\Delta V/(gc)/(Ieff)}$.[7] A decrease in PFR is coupled with an increase in Ieff and I*, and thus an increase in efficiency, as outlined in Figure 6.

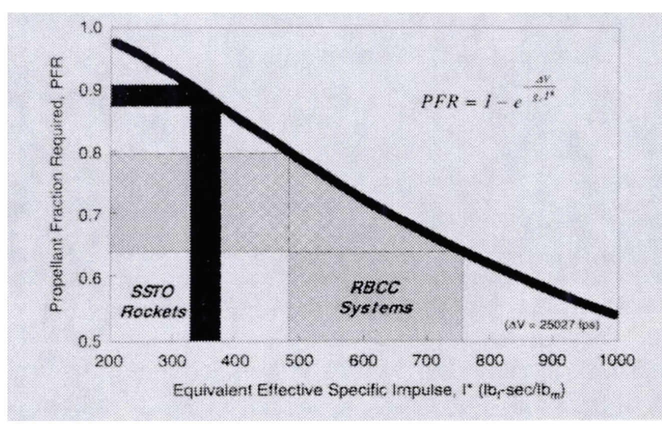

Figure 6: Effect of equivalent specific impulse (I*) on propellant mass fraction for Single-Stage-To-Orbit (SSTO) vehicles. A higher I* results in a significantly reduced propellant fraction, indicating improved efficiency and reduced fuel requirements. This relationship is pivotal in determining feasible mass limits for SSTO launch vehicles. [12]

DOI: 10.36838/v8i1.106

Rocket performance other than a stoichiometric fuel-oxidizer ratio and the performance of air-breathing propulsion designs can be described by the analytical relationships given below. “hf” is defined as the propellant heating value and is determined independently for rich and lean cases.[2]

$$h_f = 5{,}770\left[\frac{1 - f/o}{1 - f/o|_{st}}\right] + h_0 \quad \text{(rich)}$$

$$= 5{,}770\left[\frac{f/o}{f/o|_{st}}\right] + h_0 \quad \text{(lean)}$$

$$I = \frac{V_0}{g} = \frac{1}{g}\sqrt{2gJ\eta_n h_f\left[1 - \left(\frac{P_6}{P_4}\right)^{\sigma_n - 1/\sigma_n}\right]}$$

Discussion

Mathematical Comparison:

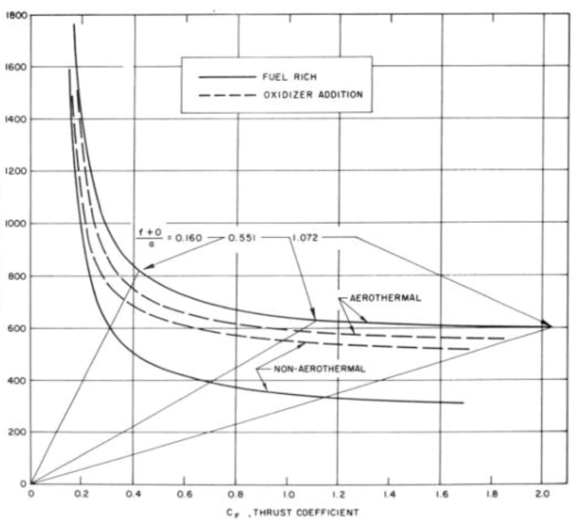

Figure 7: Comparison of thrust augmentation effectiveness for different fuel proportions. The chart shows that while increasing fuel raises thrust, it decreases specific impulse. Air-breathing engines maintain a higher specific impulse than rockets at all fuel ratios. This supports the strategic advantage of air-breathing designs in missions requiring extended propulsion efficiency.[2]

Figure 7 shows how specific impulse varies with fuel proportion. Increasing fuel boosts thrust but reduces specific impulse. Both air-breathing and conventional rockets follow similar trends, but the air-breathing design consistently achieves higher specific impulse at each fuel proportion.

HySIDE Modeling Results:

HySIDE (Hypersonic System Integrated Design Environment) incorporates complex parameters like propulsion, fuel consumption, mass, aerodynamics, and temperature effects. 1 The HySIDE program also factors variables such as Gross Takeoff Mass (GTOM), empty mass, and wetted area for efficiency comparisons.

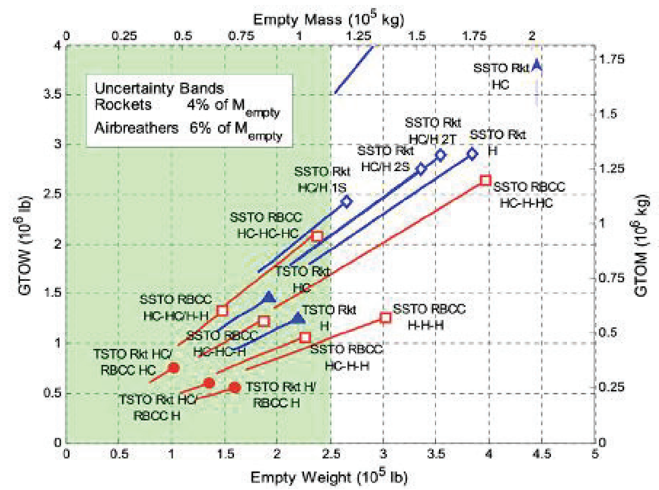

Figure 8: Reusable launch vehicle (RLV) empty mass versus gross takeoff mass (GTOM). This HySIDE model output compares multiple propulsion configurations, with air-breathing systems like the TSTO Rkt-RBCC achieving lower empty mass within practical GTOM ranges. The data suggest that hybrid propulsion systems offer optimized mass trade-offs for realistic mission profiles.[1]

Figure 8 shows the gross takeoff and empty masses for all vehicle variations. The green-shaded area marks the practical limits. Notably, air-breathing launch systems reduce empty mass, with the TSTO (Two-Stage To-Orbit) Rkt (Rocket)-RBCC being the lightest. The TSTO Rkt-RBCC is a propulsion mechanism that combines rocket ascent with air-breathing cruise. Hydrocarbon-fueled vehicles provide the highest GTOM with relatively low empty masses. It is worth noting that TSTO propulsion doesn’t apply to fixed-wing designs like the SR-71, as stage separation will render the vehicle aerodynamically unfavorable. Brittleness of Titanium alloys at lower temperatures also makes them unsuitable for TSTO applications. A comprehensive economic analysis comparing development costs, manufacturing complexity, and operational expenses would strengthen the practical assessment of these systems.

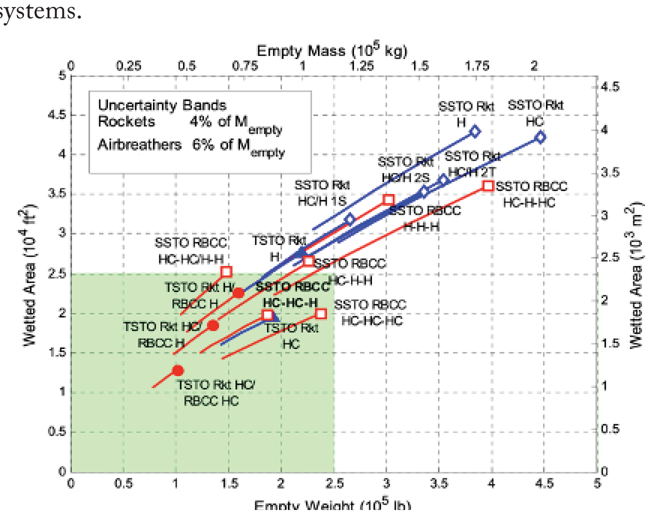

Figure 9: RLV empty mass versus wetted area. The figure analyzes aerodynamic efficiency and maintenance cost implications, indicating that higher empty mass in rocket systems corresponds to reduced wetted area, while air-breathing systems show more complex aerodynamic trade-offs. These trends emphasize the structural and operational complexity inherent to air-breathing systems.[1]

Figure 9 compares vehicles in terms of wetted area. The wetted area is a good indicator of the aerodynamic drag experienced by the vehicle upon launch and expected maintenance costs. The impact that increased wetted area can have on maintenance costs is dependent on the smoothness of the aircraft's skin surface, and may vary greatly for different materials employed in the manufacturing process. The graph shows a nonlinear relation, suggesting that rocket-based launch systems tend to decrease wetted area relative to increases in empty weight. However, it is also worth noting that most rockets with higher empty masses are beyond practicality.

Future Research

Some variations of RBCC engines function with the help of a precooler system that lowers the temperature of oncoming airflow before combustion.[6-8] Chilling the hot air allows for an extremely high-pressure ratio, increasing the thrust and efficiency of the engine.[8] This design is currently used by the SABRE engine, developed by Reaction Engines Corporation.[8]

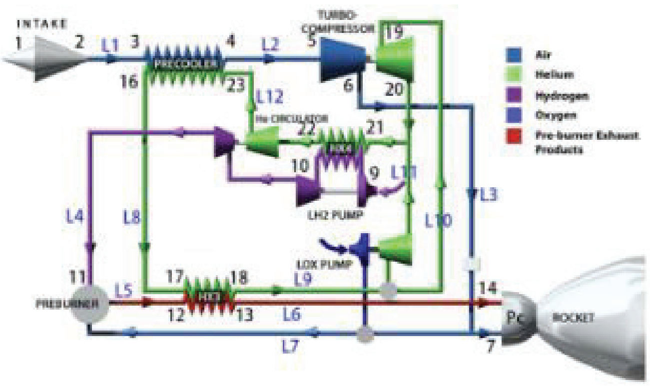

Figure 10: The precooler mechanism of the SABRE engine. The image shows the process of rapidly cooling incoming atmospheric air using cryogenic fuel, enabling operation at extreme velocities without engine meltdown. This innovation is critical in maintaining engine integrity during high-speed, high-temperature conditions.

Amar. S and Gowtham Manikant also discussed improving the design of an air-breathing rocket in "Air-Breathing Rocket Engines and Sustainable Launch Systems."[15] This design proposes implementing a Rocket Engine Nozzle Ejector (RENE). The configuration creates a shrouded area that allows for higher combustion during flight and massive gains in thrust, and also helps to improve thrust augmentation.[15]

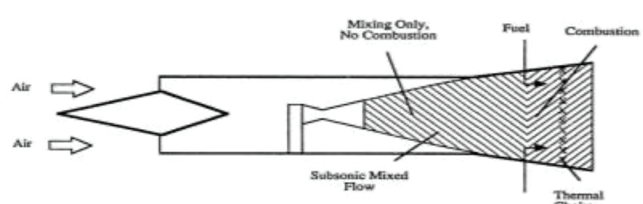

Figure 11: Air-augmented ramjet engine with thermal choke. This diagram illustrates a proposed thrust augmentation concept using a Rocket Engine Nozzle Ejector (RENE) and thermal choke to improve combustion stability and thrust at high speeds. The inclusion of a thermal choke helps mitigate instability during supersonic combustion.

Conclusion

The conclusions reached from the study indicate that air-breathing launch systems can achieve a higher fuel efficiency than rockets. Results from the HySIDE modeling analysis and those of previously published works in the field suggest that aerothermal engines are superior in specific impulses compared to their rocket counterparts. While the particular impulse values adhere to the same generic pattern across varying thrust coefficients, the quantity per given thrust coefficient is higher across all parameters, even when considering different types of fuels, SSTO vs TSTO systems, and uncertainty values associated with the calculations made.

Results also suggest that air-breathing engines have a lower total empty mass than rockets. A lower empty mass indicates a lower takeoff weight for the same amount of a given payload, thus increasing efficiency. While rocket engines can handle immensely high takeoff masses, launch vehicles of this size are outside practical operating parameters and are unlikely to be procured by space agencies.

However, air-breathing launch vehicles have a higher empty mass fraction than rockets. The empty mass fraction indicates the proportion of the total takeoff mass taken up by the weight of the vehicle itself, fuel excluded, and points to added structural complexity and overhaul costs. Moreover, aerothermal engines have a higher wetted area than rockets due to their size and technical intricacy. A higher wetted area reduces the system's aerodynamic efficiency and increases the amount of material exposed to outside elements, potentially increasing maintenance and overhaul costs.[16-18]

The optimal propulsion choice depends significantly on mission requirements, with air-breathing systems potentially favoring high-frequency satellite deployments while rockets may remain superior for deep-space missions. Air-breathing engines are more efficient from an overall perspective, while rockets have the upper hand in simplicity, robustness, and maintenance costs. However, with future technological improvements in precoolers and thermal chokes, air-breathing systems have more than enough potential to win over their rocket counterparts.

Acknowledgments

I would like to thank Professor Philip Leduc, William J. Brown's professor of Mechanical Engineering at CMU, for overseeing the project and providing valuable mentorship.

References

1. Orloff, B. S. A Comparative Analysis of Single-Stage-to-Orbit Rocket and Air-Breathing Vehicles. Master's Thesis, Air Force Institute of Technology, Wright-Patterson AFB, OH, **2006**.
2. Lindley, C. A. Performance of Air-Breathing and Rocket Engines for Hypervelocity Aircraft. In Proceedings of the 4th Congress of the International Council of the Aeronautical Sciences (ICAS), Paris, France, Aug 24–28, **1964**.
3. Merlin, P. W. Design and Development of the Blackbird: Challenges and Lessons Learned; NASA/SP-2009-4566; NASA: Washington, DC, **2009**.
4. Fry, R. S. A Century of Ramjet Propulsion Technology Evolution. J. Propul. Power **2004**, 20 (1), 27–58.

DOI: 10.36838/v8i1.106

5. Xue, H.; Khawaja, H.; Moatamedi, M. Conceptual Design of High Speed Supersonic Aircraft: A Brief Review on SR-71 Aircraft. AIP Conf. Proc. 2014, **1637** (1), 1202–1210.
6. Lakhara, K. SABRE ENGINE: Single Stage to Orbit Rocket Engine. ResearchGate, 2010.
7. Hellman, B.; Czysz, P. A.; Bruno, C. Two Stage to Orbit Conceptual Vehicle Designs Using the SABRE Engine. J. Br. Interplanet. Soc. **2016**, 69 (1), 27–39.
8. Varvill, R.; Bond, A. SABRE Technology Development: Status and Update. In Proceedings of the 8th European Conference for Aeronautics and Space Sciences (EUCASS), Madrid, Spain, July 1–4, **2019**.
9. Williams, N. A. A Performance Analysis of a Rocket-Based Combined Cycle (RBCC) Propulsion System for Single-Stage-to-Orbit Vehicle Applications. Master's Thesis, University of Tennessee, Knoxville, TN, **2010**.
10. Klink, P.; Lüdeke, H.; Klevanski, J.; Sippel, M. Investigation on the Performance and Feasibility of RBCC-Based Access-to-Space via Multi-Objective Design Optimization. Acta Astronaut. **2019**, 157, 70–83.
11. Chen, J.; Zhang, W.; Liu, Y.; Bao, W. Experimental and Numerical Study on RBCC Engines Performance in Simultaneous and Combustion Cycle. Aerosp. Sci. Technol. **2024**, 145, 108039.
12. Whitlow, W. Innovative Airbreathing Propulsion Concepts for Access to Space; NASA/TM-2001-210564; NASA: Washington, DC, **2001**.
13. Greenwood, S. Definition of Specific Impulse. In Encyclopedia of Aerospace Engineering; Blockley, R., Shyy, W., Eds.; John Wiley & Sons: Chichester, UK, **2010**.
14. Ross, F. Space System Specific Impulse. In Encyclopedia of Aerospace Engineering; Blockley, R., Shyy, W., Eds.; John Wiley & Sons: Chichester, UK, **2010**.
15. Borda, T. ATINER's Conference Paper Series MEC2020-2713; Athens Institute for Education and Research: Athens, Greece, **2020**.
16. Chernyshev, S. Modern Problems of Aircraft Aerodynamics. In Springer Aerospace Technology; Springer: Cham, Switzerland, **2019**.
17. Clark, C. The History and Promise of Combined Cycle Engines for Access to Space Applications; NASA/TM-2010-216186; NASA: Washington, DC, **2010**.
18. Yang, X. A Simplified Model for the Simulation of Synergistic Air-Breathing Rocket Engine. In Proceedings of the 32nd Congress of the International Council of the Aeronautical Sciences (ICAS), Shanghai, China, Sept 6-10, **2021**.

■ Author

Geunhyung Hong is an aspiring aerospace engineer fascinated by the science of flight, namely the pursuit of optimizing vehicle performance through advanced airflow analysis. He wants to develop innovative airframe designs that reduce drag and increase efficiency, paving the way for sustainable aviation. He hopes his efforts will contribute to the next generation of hypersonic aircraft and launch vehicles.