Exploring the Challenges Faced in Developing Hypersonic Flight

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Abstract

This paper explores the primary challenges hindering the development of hypersonic technology, focusing on thermal management, propulsion systems, and maneuverability. Hypersonic technology, defined as flight exceeding Mach 5, presents significant opportunities for advancements in both military and commercial aviation. Despite over fifty years of development and increasing investment, particularly highlighted by the Pentagon's 2025 budget request of $6.9 billion, the widespread adoption of hypersonic technology remains incomplete. The extreme heat generated at hypersonic speeds necessitates advanced materials and cooling systems to maintain structural integrity and protect critical components. Additionally, developing suitable propulsion systems, such as ramjets and scramjets, is essential for achieving and maintaining hypersonic speeds, but these systems currently face limitations in efficiency and application. Finally, the paper discusses the maneuverability constraints and radar detection issues associated with hypersonic flight, which pose significant operational challenges. The ongoing international competition, particularly with Russia and China, underscores the strategic importance of overcoming these challenges to advance hypersonic technology. The findings suggest that while significant progress has been made, further research and development are crucial to realize the full potential of hypersonic technology in both military and commercial contexts.

Introduction

This year, the Pentagon requested that the budget for hypersonic research for fiscal year (FY) 2025 be increased to $6.9 billion [8]. This is up from the request for the budget in FY2023 at $4.7 billion. With ever-rising international tensions, the race to develop more hypersonic weapons becomes increasingly urgent. Hypersonic flight is defined as flight above Mach 5. Mach number is based on the speed of sound, measured as the ratio between the object's speed and the speed of sound. Mach 1 is the exact speed of sound, around 1200 km/h in air at room temperature. The Mach number of an object varies directly based on the object's speed relative to the speed of sound. After more than 50 years of development and constant increases in research budget, hypersonic technology is not as widely used as it could be. This leads to an important question that should be considered: what challenges are faced in developing commercial hypersonic technology?

Challenges

One significant challenge that needs to be considered when understanding hypersonic flight is the management of heat. At 3300+ MPH, the air in front of the aircraft becomes highly compressed, and when combined with the immense friction between the aircraft surface and air molecules, the temperature rises dramatically. Due to this issue, sufficient thermal management tactics must be in place to handle the heat. A major component of thermal management is the shape of the aircraft itself. According to Arizona State University, aerodynamic heating plays such a critical role in hypersonic flight that it heavily influences the design of most vehicle shapes [12]. These shapes vary depending on whether the goal is to maximize or minimize drag. For reentry vehicles, like the Space Shuttle, maximizing drag is essential for deceleration, leading to blunter designs. In contrast, hypersonic cruise and acceleration vehicles, such as the X-43A pictured in Figure 1, are designed to minimize drag and extend range, leading to lowered convective heat rates. Considering this factor, a major step to strong thermal management would include the shape when designing the aircraft, providing a simple supporting step. The high temperatures also risk the internal components of the aircraft by potentially corroding the outer materials and bringing the heat inside. This means that advanced materials and cooling systems must be developed to prevent overheating and ensure the structural integrity of the aircraft.

Figure 1. X-43A.

Proper thermal insulation and heat shielding must be implemented to protect crucial electronics and components from melting or malfunctioning due to extreme temperatures. For example, NASA's Space Shuttle program included developing porous silicon tiles to be placed along the Space Shuttle's surface [7]. These insulated the shuttle and prevented any damage to the inside components. Another method proposed in a lecture involved combining factors like materials, cooling techniques, and system requirements [2]. When dealing with fuel flow, choosing the correct type of fuel would be key to cooling the engine due to the development of fuel flow cooling, where the fuel itself would be used to cool the engine while traveling through the fuel lines. The lecture mentions, "Hydrogen is the best fuel for scramjet, considering the heat release and the cooling capability” [2]; however, hydrogen’s low density results in inefficient storage.

To achieve hypersonic speed, regular turbofan/turbojet engines are not used mainly due to the high speeds causing shockwaves and high pressure within the compressor and the air moving too fast to mix with the fuel properly. Turbojets are generally used for supersonic speeds up to Mach 3, as they are less efficient than turbofans at subsonic speeds. This is explained best by Caltech Ph.D. graduate Kim Aaron: “You can get the same thrust by accelerating a small mass of air to high speed or a large mass of air to a slower speed. A jet engine does the first thing. A turbofan does the second thing. They can both produce the same thrust. The difference is that the energy needed to get the smaller mass of air going faster is greater than the energy needed to increase the speed of the larger mass of air by a small amount” [1].

It is important to note that with the right engine inlet design, the shockwave creator on the turbojet blades will be reduced as long as the inlet reduces the incoming airflow to a subsonic speed, which would eliminate the shockwaves. Turbofans are primarily used in subsonic flight and in most commercial jets. Turbojets (shown in figure 2) and turbofans (shown in figure 3) work similarly [5]. Initially, they intake air at the engine's inlet and send it through the compressor. The compressor consists of several fan blades which move the air at high speeds to compress it [3]. The air is then sent through the combustion chamber, mixed with jet fuel, and ignited. This hot air is sent through the turbine, another set of fan blades similar to the compressor, expanding the gas rather than compressing it. This combusted gas exits rapidly through the nozzle, creating forward momentum and thrust, propelling the aircraft forward. While turbojets and turbofans work very similarly, one fundamental difference exists: a turbofan has a much greater bypass ratio than a turbojet does, meaning the inlet for turbofans is much larger, and therefore, they intake much greater volume of air than turbojets do. This is why turbofans cannot be used in supersonic flight. The fan blades are too long to produce enough thrust to fly at supersonic speeds safely. The fan would be spinning at such a speed that the ends of the fan blades would be traveling at supersonic speed, sending shockwaves along the fan and inside the engine, risking severe structural damage to the engine.

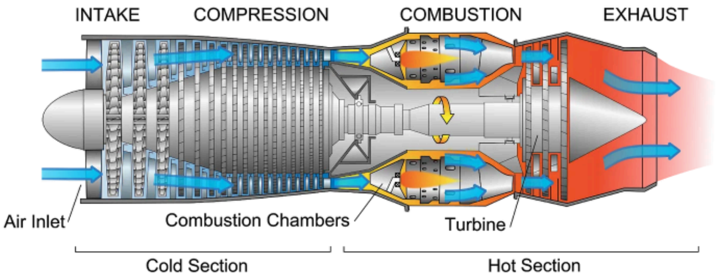

Figure 2. Turbojet Engine Cross-section with Labeled Sections.

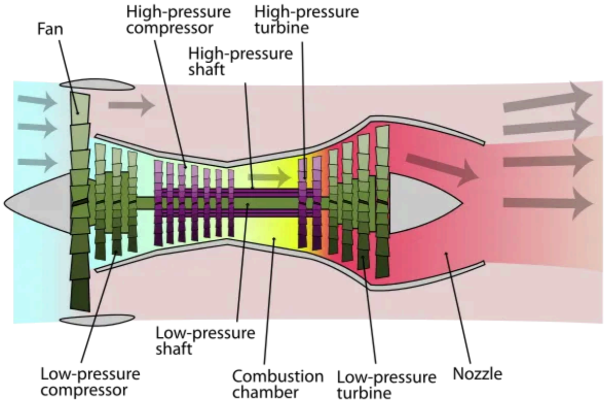

Figure 3. Turbofan Engine Cross-section with Labeled Sections.

Special engines called "Ramjets, " illustrated in figure 4, must be used to fly at hypersonic speeds effectively. Ramjets work by using the outside air "ramming" into the engine at high speeds and into the combustor [6]. Unlike a turbojet, ramjets do not have compressors; instead, the high speed of the air compresses it within the narrow combustor. This air exits the engine with such force that it creates enough thrust to propel the aircraft to hypersonic speeds.

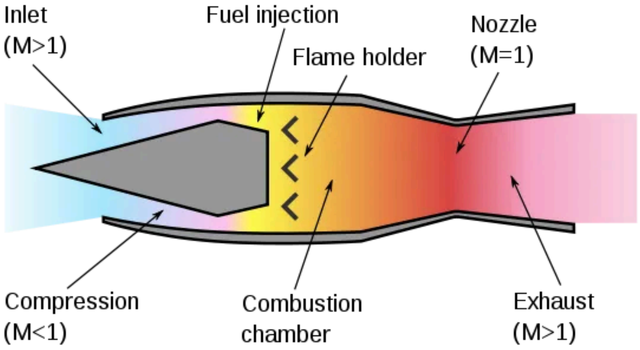

Figure 4. Ramjet Engine Cross-section with Labeled Sections.

However, ramjets become very inefficient above Mach 5 because air must move at subsonic speeds within the combustor, and slowing the supersonic/hypersonic air down to a subsonic speed within the engine alone is a major challenge. Figure 5 represents this relationship graphically; the specific impulse is the efficiency of thrust creation. More specifically, it measures an engine's fuel mass usage efficiency for thrust creation: a higher specific impulse means a higher efficiency. At Mach 5, a ramjet's specific impulse tends to decrease.

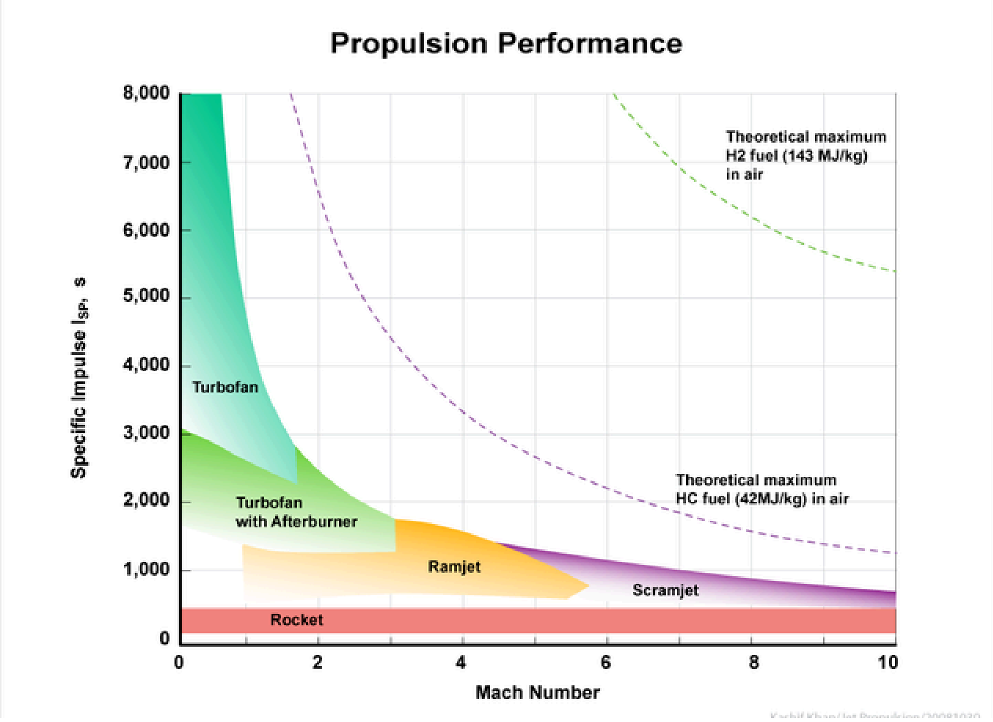

Figure 5. Performance Chart of Different Engines Based on Specific Impulse and Mach Number.

To solve this issue, a supersonic combustion ramjet, or scramjet, was designed to allow for combustion at supersonic speeds [4]. Scramjets are used in hypersonic flight, generally in the upper atmosphere. They work by having a constant stream of air flowing through the engine, allowing for continuous combustion and thrust generation, illustrated in Figure 6 below.

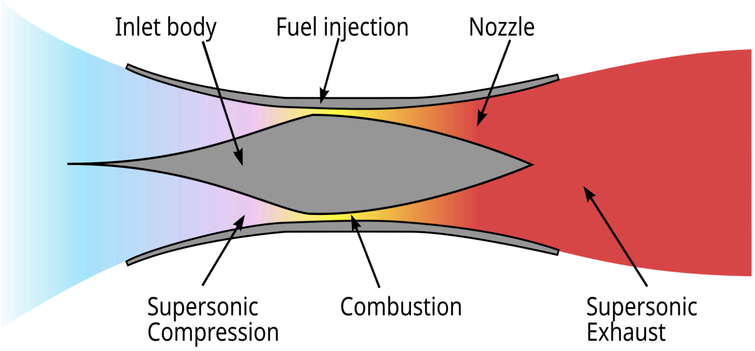

Figure 6. Scramjet Engine Cross-section.

Because ramjets/scramjets rely on air already entering the engine at high speeds, they cannot produce thrust on their own, as there are no moving parts. They must have another system, generally a booster rocket, to get them up to speed to produce an efficient amount of thrust [10], as seen in Figure 5. Most aircraft, like missiles, traveling at hypersonic speeds will be propelled with a booster phase until it is in the upper atmosphere, at this point, the missile would re-enter the atmosphere and utilize the ramjet/scramjet engine. This system is known as a “boost-glide” system and has advantages over the parabolic paths that ballistic missiles use. Scramjets can reach speeds up to Mach 15 or higher, making them ideal for high-speed military and research aircraft. Despite their efficiency at hypersonic speeds, scramjets are still in the experimental stages and have yet to be widely implemented in commercial aviation. However, continued advancements in engine technology may soon lead to a new era of faster and more efficient air travel.

While in hypersonic flight, aircraft (namely missiles) tend to have several significant operational challenges, including maneuverability issues, system communications, and increased radar detection. Regarding maneuverability, three central components must be considered: range, speed, and altitude. At hypersonic flight, speed is not as much of an issue as the other two components because the aircraft is already moving so fast, but this leads to the issue of agility. At speeds upwards of Mach 10, HCMs (hypersonic cruise missiles) require a turning radius of about 120 kilometers. Because of this limitation, it is very difficult for hypersonic missiles to quickly change course if it would need to. Additionally, the heat produced by the aircraft significantly raises the level at which heat-detecting radar can detect the aircraft. This threatens the aircraft and makes defenses much easier, which is a driving factor for why the U.S. military would want to develop an effective thermal management system.

Alongside the technical reasons, there are also economic and political implications behind why the U.S. military would want to continue developing hypersonic technology. The U.S. has competed with Russia and China for decades to maintain the most international power. According to The Association Of The United States Army, Russia, China, and North Korea have all successfully tested hypersonic missiles, mentioning that “The hypersonic threat is not only from China; Russia has successfully tested a naval hypersonic missile, the Zircon, and North Korea claims to have tested a hypersonic missile,” [13]. The international tensions between these nations and the U.S. are a significant motivator for the continuing development of hypersonic technology. Currently, hypersonic missiles are more expensive to produce than ballistic missiles, mainly due to the increased complexity in design that comes with heat management. As the U.S. Congressional Budget Office (CBO) describes it, “Specifically, CBO estimates that procuring 300 intermediate-range hypersonic boost-glide missiles like the ones being developed by the Army and the Navy and then sustaining the missile system for 20 years would cost a total of $17.9 billion in 2023 dollars . . . By comparison, 300 MaRV-equipped ballistic missiles with the same speeds, ranges, and targeting capabilities as those hypersonic missiles would cost a total of $13.4 billion, CBO estimates,” [11]. This further pushes the need to find a more affordable way to develop hypersonic missiles without sacrificing design integrity.

Conclusion

Standardizing hypersonic travel in the aviation field is very difficult, as many issues exist. With more funding from the government, the military and other organizations may be able to speed up and improve hypersonic aircraft research. This involves the further development of heat management, development, and procurement costs, all while maintaining a controlled international situation. However, if hypersonic travel is developed enough, it can reach a point where its flight capabilities would exceed and outperform regular current flight capabilities, both technologically and economically, and potentially be used in commercial aviation.

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