IMPROVING THE EFFICIENCY OF THE HYPERSONIC PRECOOLED COMBINED CYCLE ENGINE (HPCCE)

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Abstract

The idea of the Hypersonic Precooled Combined Cycle Engine (HPCCE) encompasses a wide variety of aircraft engines, though at a fundamental level, this terminology refers to an engine in which multiple operating modes are used to propel the aircraft with a single flowpath (Takeshi). Such an engine is used to propel an aircraft to hypersonic speeds, speeds that are typically defined as above Mach 5, or about 1,715 m/s. Some of the most efficient rocket designs involve using liquid hydrogen as fuel, due to it yielding the highest specific impulse, the use of a scramjet engine to use supersonic airflow in combustion, and lightweight, high-temperature alloys such as Inconel X alloys. These features, when combined and configured with specific parameters for engine size, fixed temperatures of components, and a unique fuselage, can comprise a highly efficient hypersonic aircraft that could be more powerful than the state-of-the-art. The goal of the work done here is to identify the key traits in a hypersonic aircraft that, if adjusted, can increase the power, speed, and efficiency of the aircraft, the last of which is typically measured in specific impulse.

Background

Some alternative rocket designs have been considered and some are under development, particularly some that use nuclear thermal propulsion or nuclear electric propulsion. Upon considering the energy output of a nuclear system, NASA has made it clear that "the fundamentals of nuclear propulsion can enable robust and efficient exploration beyond the Moon" (Skelly). Though nuclear based propulsion seems like a viable option for hypersonic and space travel, the technology does not yet exist to start building such a platform. There have been several advances in improving the efficiency and power of hypersonic aircrafts. Perhaps the most notable of these developments has been the work towards the SABRE rocket engine design. Although this concept is not fully completed, it consists of a precooled combined cycle engine, operating in two modes, one consisting of an airbreathing turbo jet engine and the other using a traditional rocket engine ("SABRE"). Precooling techniques are actively discussed in this field, as precooling the ambient air, and controlling the temperatures of engine components allows for more efficient combustion, and thus a higher specific impulse for the aircraft. There is work being done to try to 3D print (micro-manufacture) compact heat exchangers to allow for precooling the engine components and air intake (Meng). It is worth noting that the fastest hypersonic aircraft in history is the X-43, achieving a maximum velocity of Mach 9.6, and the X-15 is the fastest manned aircraft in history, achieving a maximum velocity of 6.7. Both of these served as an inspiration for the work conducted in this project.

References

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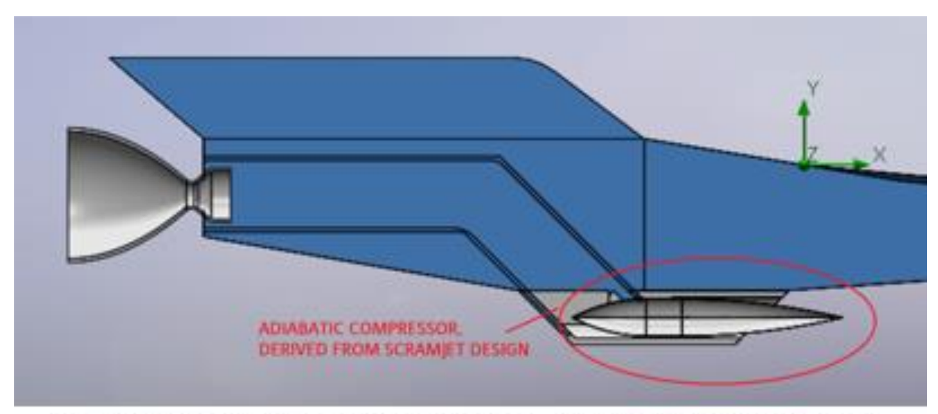
Methodology and Analysis

In order to understand how an aircraft can operate at hypersonic speeds, and how the power can be maximized, an aircraft was modeled from scratch in SolidWorks. This approach ignores flight for a specific purpose other than to test efficiency for flight at hypersonic speeds above anything achieved currently, as well as to obtain a deeper understanding of the critical determinants of efficiency and thrust in an engine design. In this design, only the bare minimum components of the aircraft have been included in order to display, at a fundamental level, how a hypersonic aircraft functions, and how efficiency and power can be increased by adjusting various components after isolating them from the full assembly.

The first major design decision was the form of the combined cycle engine, and more specifically, the shape of the nozzle. Taking inspiration from some of the fastest aircrafts in the world, including the X-15 and the X-43, the aircraft in this study incorporated two of the most important propulsion features from each of the aircrafts: the rocket engine, and the scramjet compressor. For the rocket engine, a parabolic bell-shaped nozzle was selected, as this is often regarded as the most optimal design, as it does not restrict the expansion of the exhaust gases (Braeunig). In addition, a scramjet compressor was attached to the engine in order to pressurize the ambient air intake, so that combustion of the liquid hydrogen propellent could occur at a lower temperature. The aircraft was designed to be air-breathing so that it would not have to carry the added weight of the oxidizer.

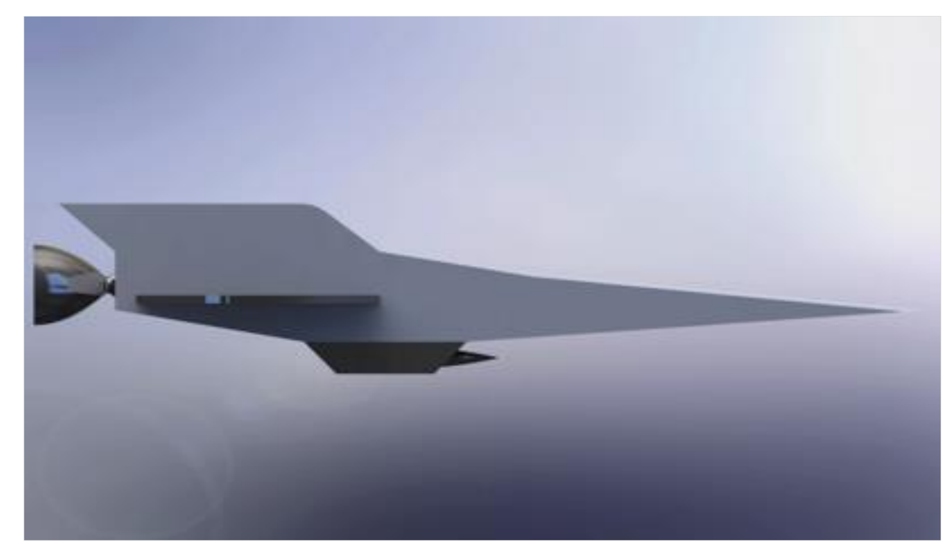
Using an Excel spreadsheet with a multitude of thermodynamic and kinematic equations, the maximum velocity, maximum altitude, and specific impulse of the aircraft was able to be computed for specified angles of attack.
The engine has a burn time of 25 seconds and is capable of traveling at a maximum of about 18,500 m/s. If an extremely high angle of attack is used, such as 25 degrees to the horizontal, the aircraft can reach outer space in roughly 151 seconds. The aircraft produces a maximum specific impulse of 1540 seconds.

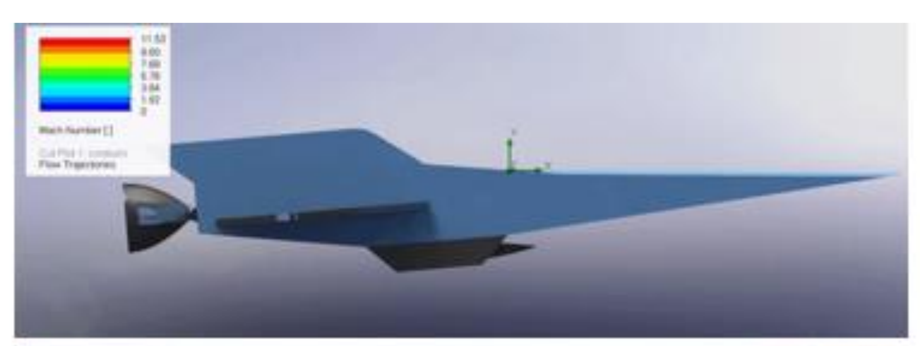


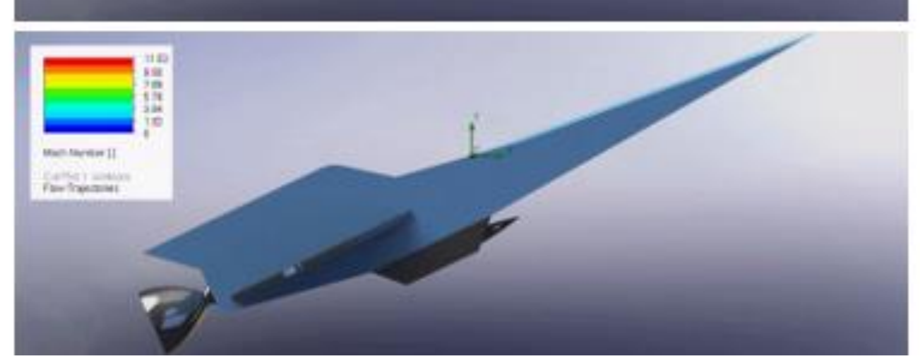
The compressor on the model is similar to that which is used on a scramjet engine, such as the one located on the X-43. It is a simple adiabatic compressor which relies on the following set of equations:

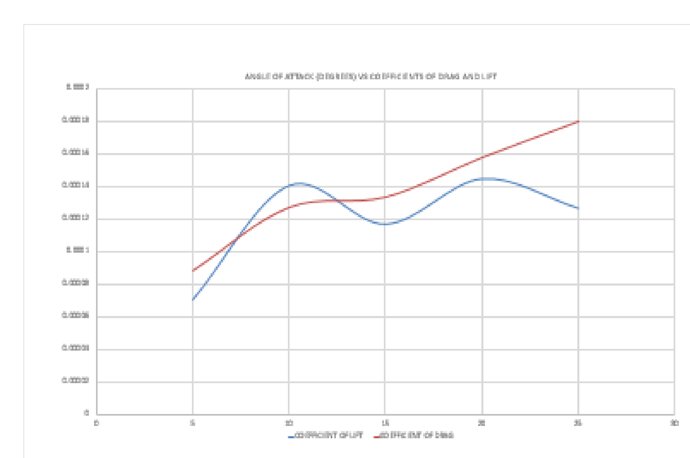
$$CPR = (Tt_1 / Tt_2)^{\gamma/(\gamma-1)} \text{ and } CW = ((c_p\, Tt_2) / (\eta_c))\,(CPR^{(\gamma-1)/\gamma} - 1)$$

Inputting the calculated compressor pressure ratio (CPR) into the compressor work per mass (CW) equation on the right, the efficiency of the compressor is rated at roughly 20%. Because the compressor does not use any mechanical parts, and the change in temperature is relatively small, it has a low efficiency.









Discussion

Through our analysis, it can be observed that it is relatively simple to achieve flight at high Mach numbers, by creating a powerful thrust and limiting the number and size of extraneous components in the aircraft. Simplifying the combustion process by allowing the engine to be airbreathing (scramjet) allows for less fuel to be carried, and thus a lower mass needing to be propelled. In addition, decreasing the temperature of combustion by decreasing the oxidizer-to-fuel ratio allows for a higher total mass flow rate. This is because although the mass flow rate of fuel (LH2) is higher with a higher combustion temperature, the o/f ratio is lower, and thus the mass flow rate of the oxidizer part is lower, which according to the ratio, makes up a larger part of the total mass flow rate. In other words, less fuel is carried onboard and the temperatures of the intake, combustion chamber, and exhaust are regulated to specific values in order to ensure the o/f ratio is maintained and the required thrust is produced to propel the aircraft at the desired speed.

The maximum specific impulse of the aircraft is about 1540 seconds, which is considerably higher than other notable rocket engines, namely the X-15 with a specific impulse of about 276 seconds or the Saturn V's 2nd and 3rd stage with a specific impulse of about 421 seconds.

Conclusions and Directions for Future Research

Upon researching this topic, it is safe to conclude that temperature, pressure, materials, and the size of engine orifices determine the maximum velocity of the aircraft as well as the efficiency of the aircraft. The model created for this presentation is an example of a combination of initial parameters that can allow for hypersonic flight above Mach 9.6 speeds, which are regarded as the highest speeds achieved by an aircraft in hypersonic flight. Some key conclusions were drawn through the construction of such an aircraft: constricting airflow through a smaller nozzle allows for a lower mass flow rate, which can allow for a longer burn time. An aircraft of this kind would require equipment to sustain flight at speeds up to almost 18,500 m/s. The velocity of the aircraft can be throttled down by reducing the throat size of the rocket engine. This can also be done by increasing the temperature of the combustion chamber, though this would result in a lower specific impulse, and therefore, a lower efficiency.

Some questions that remain unanswered are the type of aerodynamic heating the fuselage of the aircraft would experience particularly during reentry, though it is safe to assume based on previous flights taken by rockets and aircrafts such as the X-15 that the Inconel X alloy would be able to withstand these temperatures, perhaps with the aid of an ablative coating. In order to further this work, a design would have to be made for heat exchangers between the fuel and various parts of the engine and intake in order to maintain the temperatures specified. In addition, this design could serve as a foundation for more complicated aircrafts intended for interstellar travel, perhaps depending on some form(s) of electric propulsion upon exiting Earth's orbit.

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