The History and Promise of Combined Cycle Engines for Access to Space Applications

Motivating Undergraduates in Science and Technology (MUST) Research Paper

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Summer 2010
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Abstract

For the summer of 2010, I have been working in the Aerodynamics and Propulsion Branch at NASA Dryden Flight Research Center studying combined-cycle engines, advanced propulsion technology. Combined cycle engines integrate multiple propulsion systems into a single engine capable of running in multiple modes. These different modes allow the engine to be extremely versatile and efficient in varied flight conditions. The two leading examples of combined cycle engines are Rocket-Based Combined Cycle (RBCC) and Turbine Based Combined Cycle (TBCC). The RBCC essentially combines a rocket and ramjet engine, while the TBCC integrates a turbojet and ramjet[1]. These two engines are able to switch between different propulsion modes to achieve maximum performance. Extensive conceptual and ground test studies of RBCC engines have been undertaken; however, an RBCC engine has never, to my knowledge, been demonstrated in flight. RBCC engines are of particular interest because they could potentially power a reusable launch vehicle (RLV) into space. The TBCC has been flight tested and shown to be effective at reaching supersonic speeds, most notably in the SR-71[2].

Substantial work remains on combined-cycle engines, especially on further testing of the RBCC engine concept. It is my goal this summer to develop a comprehensive whitepaper advocating for the continued study of combined-cycle engines, with a focus on RBCC. To do this, a study of previous RBCC and TBCC research was completed. Based on this research, I have chosen to model the Marquardt Ejector Ramjet RBCC in the Graphical Engine Analysis Tool (GECAT), due to the availability of ground test data. Once I complete an accurate GECAT model, the comparison between a real RBCC engine and current modeling software data will be compelling evidence for the potential of RBCC engines. I will then complete a trajectory analysis using a software tool known as Program to Optimize Simulated Trajectories (POST), which will simulate the flight path of a spacecraft with a combined cycle propulsion system to

analyze the feasibility of the mission. Finally, I will begin investigating what resources Dryden Flight Research Center has available to contribute to combined-cycle engine research, and how it aligns with Dryden's mission.

Introduction

The concept of combined-cycle engines dates back to the 1950's with the first run of the SR-71's power plant, the J-58 TBCC engine[1]. Soon after, NASA funded the landmark Marquardt study, where 36 different engines, most of which were RBCC, were conceptually analyzed. Their results showed that combined-cycle engines were considerably more efficient than rockets at reaching high speeds[3]. They used their results to design and test a subscale model of an ejector ramjet, an early RBCC concept. The Marquardt ejector ramjet engine consisted of an inlet, a primary rocket section, a mixer, a diffuser, an afterburner, and an exit nozzle. At low Mach numbers, the engine essentially functions as an air-augmented, or ducted, rocket. At higher Mach numbers, the primary rocket section may be turned off, and the inlet, diffuser, afterburner, and exit nozzle system functions as a conventional ramjet engine[4].

After the successful demonstration of the multi-stage rocket system that culminated in propelling the Apollo 8 spacecraft to lunar orbit in 1968, the development of combined-cycle engines slowed. In the mid-1980's interest in alternative access to space methods re-surfaced, and several RBCC programs were initiated, including the X-30 National AeroSpace Plane (NASP), NASA's Advanced Reusable Technologies (ART) Program, and NASA's Highly Re-usable Space Transportation (HRST) Program[5]. The trend continued into the new millennium with several programs, including NASA Glenn's GTX program, and NASA Marshall's ISTAR Project. The GTX and ISTAR programs each developed a re-usable launch vehicle concept that could achieve low earth orbit (LEO)[6,7]. Unfortunately, all of the aforementioned projects were cancelled before ground testing occurred, and all were cancelled before flight testing.

Goals and Purpose

The vision of NASA Dryden is to "fly what others only imagine". The Aerodynamics and Propulsion Branch at NASA Dryden continues this commitment with cutting-edge research on innovative propulsion concepts. Dryden has both the research and operational capabilities to study and flight test combined-cycle engines. Once completed, my paper will include the history of RBCC and TBCC engines, a model of an RBCC engine, and a discussion on the comparison between ground tests and modeling data. This will serve to advocate for further combined-cycle research at Dryden.

The RBCC engine provides an alternative to conventional multi-stage rockets for access to space, and normally consists of air-augmented rocket, ramjet, scramjet, and pure rocket modes. A typical concept will be single-stage-to-orbit (SSTO) or two-stage-to-orbit (TSTO). Since a ramjet is not capable of producing static thrust, a SSTO RBCC concept will begin operating in an air-augmented rocket mode until the airflow through the engine is fast enough for the ramjet to work efficiently. The ramjet then takes over until supersonic combustion occurs, at which point the engine switches to scramjet (supersonic combustion ramjet) mode. Once the air becomes too thin for the scramjet to remain active, the engine reverts to a pure rocket mode and propels the vehicle into orbit. A TSTO engine concept operates in the same manner, except that a first-stage rocket or carrier aircraft is used to increase the airflow enough for the ramjet to become active[1].

A TBCC engine is essentially a combination of the turbojet and ramjet engine cycles. As in an RBCC, the airflow through the engine must be accelerated for proper ramjet operation. This is achieved by beginning in a turbojet mode until the appropriate speed is reached. Materials and design constraints at higher speeds reduce the efficiency of the turbojet; so much of the airflow bypasses the turbojet assembly and flows directly to the ramjet. At this point, the ramjet produces most of the engine thrust[1]. The TBCC is a proven high speed engine concept, as two TBCC engines propelled the SR-71 to Mach 3+, making the SR-71 the fastest air-breathing aircraft to take off under its own power[2].

Combined cycle engines offer many benefits, including increased efficiency. Generally, as the amount of thrust an engine can produce increases, its efficiency decreases. Combined-cycle engines can operate in the most efficient mode for the present flight condition, thereby increasing the efficiency of the engine unit over the ascent profile as a whole. This is what makes the RBCC engine particularly interesting for space transport applications. A conventional rocket system produces a large amount of thrust to quickly accelerate a vehicle, but it is extremely inefficient at lower Mach numbers and altitudes. As a result, huge multi-stage rockets must be produced to propel a relatively small craft. In most current RBCC engine concepts, the engine is air breathing until the rocket mode takes over at around Mach 11[6]. This replaces a large, inefficient rocket burn at the beginning of the ascent with a much more efficient air-augmented rocket, ramjet, and scramjet operation until the vehicle reaches the upper atmosphere.

The reduction of oxidizer and fuel needed could potentially lead to a huge weight, and therefore cost, reduction. Currently, it costs thousands of dollars to get one kilogram of payload into space. This cost is, unfortunately, an immense disincentive for commercial, science, and exploration missions. RBCC engines provide a distinctly cheaper alternative. In the late 1990's, the Highly Reusable Space Transportation (HRST) program, a study that further investigated the feasibility of TBCC and RBCC engines as a means to achieve LEO, projected payload delivery to less than $400 per kilogram of payload[8]. With this cost reduction, a dramatic rise in space missions is possible.

Impact of the MUST Internship on my Career Goals

My internship at Dryden has further inspired and motivated me to continue pursuing a degree in Aeronautics and Astronautics at the University of Washington. I came to Dryden with an appreciation of military and concept aircraft, and immediately gravitated to Dryden's vision of flying what others can only imagine. I was further pleased to be placed in the Aerodynamics and Propulsion Branch, as my previous exposure to these two topics had been limited.

My lack of traditional classroom instruction in propulsion also presented a challenge. I began with reading about the different types of propulsion systems related to combined cycle engines – turbojets, ramjets, scramjets, and rockets. I learned how they work, what type of aircraft they are normally associated with, and their limitations. During this time, I also attended lectures on basic aerodynamics and propulsion. After getting a solid background, I began delving into the history of combined cycle engines, RBCC specifically. I combed through technical documents on the NASA servers, and old binders. After developing an understanding of the past research, I started solving ideal and real ramjet and turbojet propulsion problems from a textbook. Having not yet taken a propulsion class, I learned how to solve for key parameters, such as thrust, by hand. I then modeled the problems in GECAT to become familiar with the program.

Currently, I am modeling the Marquardt ejector ramjet subscale ground test engine using a1968 published report. Modeling this engine has proven to be challenging, and has required trying multiple methods and software tools. The mentoring component of the internship has been extremely helpful with this challenge. I have a mentor and an "unofficial" mentor guiding me on the project who are always willing to sit down and explain concepts or help troubleshoot reasons why the model isn't displaying favorable output data. They are able to present me with difficult problems without it being overwhelming, and I am always comfortable going to them for help. My experience at Dryden has been very positive, and I am thankful for the opportunity.

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