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Combined Rocket and Airbreathing Propulsion Systems for Space-Launch Applications

Russell Daines*
Brigham Young University, Provo, Utah 84602
and
Corin Segal†
University of Florida, Gainesville, Florida 32611

A review of rocket-airbreathing combined-cycle propulsion systems for Earth-to-orbit applications is presented. Rocket-based combined-cycle (RBCC) engines take advantage of the synergistic interactions between the rocket and the airbreathing elements of the engine and the use of high-specific impulse cycles to yield a mission-averaged specific impulse that is higher than all-rocket technology can provide. An overview of the multimode operation is given, along with a review of both experimental and modeling work that has been done on this class of engines. Selected issues involved with these engines are discussed. These include engine/vehicle integration, flow-path design for multimode operation, fuel selection, mixing enhancement and afterburning in rocket-ejector mode, thermal choking, and flameholding. RBCC propulsion is becoming recognized as a promising technology for achieving a significant reduction in the cost of delivering payload to orbit.

Introduction

CURRAN[1] points out that no single existing class of engines provides a high enough thrust-to-weight ratio to support flight over an extended Mach number range and possesses a high specific impulse over the entire range. Individual airbreathing cycles operate over only a portion of the Mach number range, as shown in Fig. 1. Rockets provide the thrust-to-weight ratio necessary and can operate over the entire Mach number range, but at a relatively low specific impulse.

Figure 1 shows the speed regimes where various propulsion cycles are preferable from a specific impulse standpoint, with gas turbine-based cycles superior up to around $M = 2$–3. Ramjet mode is most efficient from there up to about $M = 6$, and scramjet cycles are superior in the upper Mach number regime. The use of tanked oxidizer in rocket cycle, which causes the low specific impulse for the cycle, makes it well-suited to operate for final insertion into orbit for transatmospheric flight. In spite of the low specific impulse, the rocket cycle is also advantageous as an initial booster because of its high thrust-to-weight ratio, with an increase in specific impulse possible when used in rocket-ejector mode.

Historically, multiple-staged vehicles have been designed to operate with a single type of propulsion system for each stage. Stages are optimized for different altitude/Mach number regimes in the trajectory, increasing the overall system specific impulse. As an example, NASA's recently proposed hypersonic aircraft demonstrator, Hyper-X, will use subsonic aircraft propulsion as the first stage, followed by a second stage provided by a Pegasus (first stage) rocket, with the scramjet-based research vehicle as the third stage.[2] This limited-range accelerator begins its autonomous flight at $M > 5$.

The low specific impulse of rocket-based vehicles along with the use of expendable stages results in a high cost per pound to deliver payload to orbit. A major goal driving current space propulsion research is to significantly decrease the cost of access to space. There are currently efforts underway to develop reusable launch vehicles that promise to decrease long-term costs as compared to the traditional expendable staged vehicles. One way to avoid expendable staging and make use of more efficient engine cycles during part of the ascent to orbit is by using two or more separate propulsion systems on the vehicle that operate independently. These are referred to as combination propulsion systems (CPS). An example of this is the rocket–ramjet, which uses a rocket booster to achieve the initial acceleration to speeds capable of sustaining ramjet operation.[3] At that speed, the engine switches to ramjet operation for the remainder of the flight. Although the use of CPS avoids propulsion system integration issues, it requires carrying at least one propulsion system that is not actively participating in propelling the vehicle.

Another way to use high-efficiency airbreathing cycles during ascent in a reusable system is through the use of combined-cycle propulsion (CCP) systems. Combined-cycle propulsion systems can be broadly divided into two categories: airbreathing combined-cycles that could include turbojet or turbofan cycles, and combined-cycle systems that include a rocket subsystem. Examples of airbreathing CCP systems are the dual-mode combustion ramjet, which operates in both ramjet and scramjet modes,[4] and the turbine-based combined-cycle engine, which uses a turbine-based cycle for low-speed flight along with ramjet and scramjet modes.[5] Airbreathing combined-cycle engines are intended primarily for missions involving high-speed cruise in the atmosphere, but are not candidates for transatmospheric flight.

While there are many types and variations of CCP systems, one class of rocket-based CCP systems shows promise for Earth-to-orbit (ETO) missions. These are engines that operate in rocket-ejector mode and also have the capability of operating in ramjet, scramjet, and rocket-only modes, and are typically referred to as rocket-based combined-cycle (RBCC) engines. One variant is the ejector scramjet engine (Fig. 2). The ejector scramjet concept was identified by system studies to be one of the most promising for meeting the study goals as pro-

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*Assistant Professor, Mechanical Engineering Department. E-mail: dainesr@et.byu.edu. Member AIAA.

†Assistant Professor, Department of Aerospace Engineering, Mechanics and Engineering Science. E-mail: cor@aero.ufl.edu. Member AIAA.

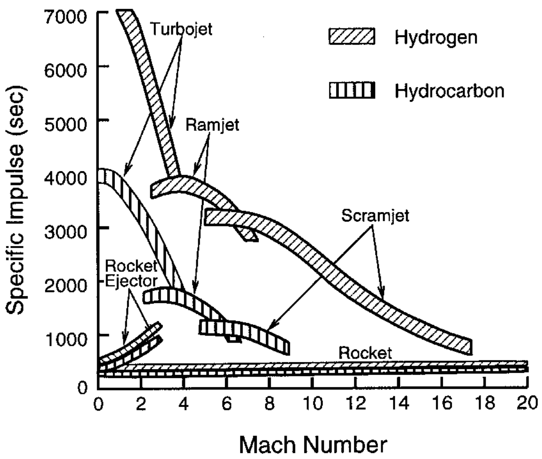

Fig. 1 Approximate specific impulse performance of different propulsion cycles.

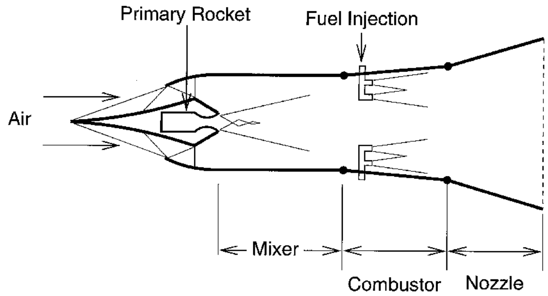

Fig. 2 Schematic diagram of an RBCC engine.

pulsion systems for both single-stage-to-orbit (SSTO)[6] and two-stage-to-orbit (TSTO) vehicles.[7]

Many of the advantages of RBCC engines result from certain synergistic benefits that would not occur if the two units operated separately.[6] The ability to utilize the rocket as an ejector increases the thrust. Afterburning in rocket-ejector mode, using the ramjet/scramjet fuel injectors, further increases the thrust and specific impulse compared to the rocket alone. As the ratio of the bypass air to the rocket exhaust mass flow increases with increasing flight speed, the specific impulse continues to increase as the cycle more closely resembles ramjet operation. In ramjet and scramjet modes, the rocket could be advantageously used as a fuel injector and mixing enhancer. In the rocket-only mode, the use of the engine duct as a highly expanded nozzle at high altitudes increases the specific impulse of that mode of operation. Another key advantage of RBCC systems is the reduction in the amount of onboard oxidizer required. This decreases the size and, therefore, the weight, of the tank and vehicle. Vehicle propellant mass fractions for RBCC-powered vehicles are projected to be around 70%, as compared to 90% for all-rocket vehicles.[8] In the rocket-ejector mode, RBCC systems can provide vehicle thrust-to-weight ratios greater than one and are therefore capable of vertical takeoff and landing. Finally, the cryogenic fuel can be used in airbreathing modes as a heat sink to increase the density of the inlet airflow, thus increasing the work output.

The focus of this review is on technical issues related to CCP systems for space-launch application, primarily RBCC systems. In the following sections an overview of RBCC operation is presented, including a review of research to date, followed by a discussion of general technical issues related to these engines. Finally, mode-specific technical issues that require further research will be outlined.

Overview of Rocket-Based Combined-Cycle Systems

Modes of Operation

The ejector scramjet (Fig. 2) is one of the most promising RBCC configurations and is the basis for a class of RBCC engines. It consists of a rocket subsystem inside an airbreathing engine with an inlet, mixer, combustor, and nozzle. Fuel injections sites may also be located in the duct. The ejector scramjet operates in four modes (Fig. 3): rocket-ejector, ramjet, scramjet, and rocket-only mode. Rocket-ejector mode (Fig. 3a) is an ejector cycle with the rocket acting as the primary or drive jet. The thrust of the rocket is augmented through a jet-pumping process that transfers momentum from the high-velocity rocket exhaust to the inducted air. The ejector process results in an increased total mass flow with a lower exit velocity and yields a higher specific impulse as compared to rocket-only operation. The rocket-ejector mode is used from takeoff through low supersonic flight speeds. Specific impulse is typically augmented by 10–20% at static conditions, and the augmentation increases to levels up to 250% at Mach numbers between 2 and 3.[6,9] Much of the thrust augmentation is accomplished in the rocket-ejector mode by afterburning fuel with the inducted air in the duct downstream of the rocket.[9]

At a flight Mach number around 3, the engine transitions to ramjet mode (Fig. 3b) provides a higher specific impulse in the mid- to high-supersonic flight speed range. Oxidizer is supplied by the ram air from the inlet, and combustion takes place subsonically. At about $M = 6$, operation of the engine is switched to the scramjet mode (Fig. 3c), where combustion takes place in a supersonic flowfield. The engine combustor flow path must be straight or divergent in this mode to avoid unwanted thermal choking in the scramjet. The rocket is either shut off or used as a fuel injector in both ramjet and scramjet

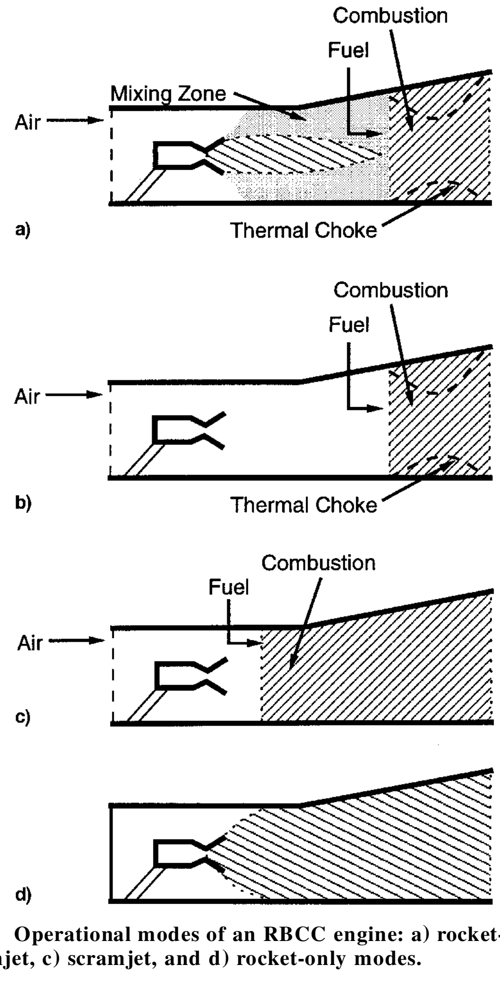

Fig. 3 Operational modes of an RBCC engine: a) rocket-ejector, b) ramjet, c) scramjet, and d) rocket-only modes.

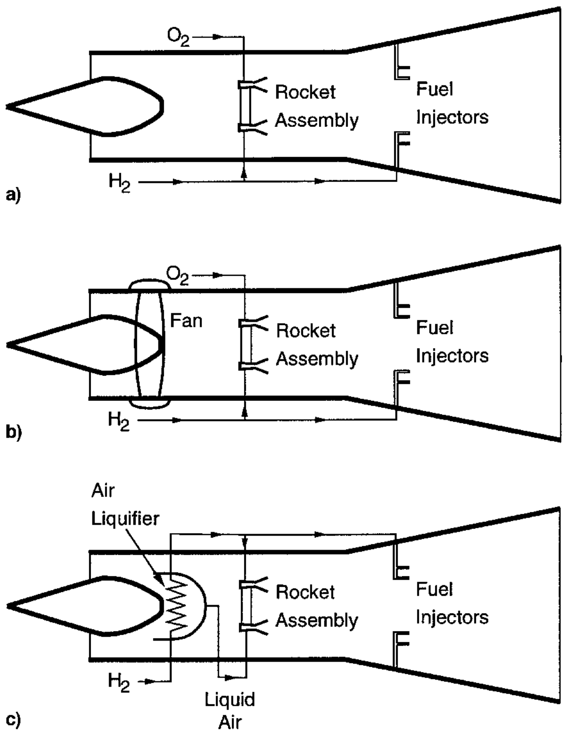

Fig. 4 Schematic diagram of possible subsystems that could be added to the ejector scramjet engine: a) basic ejector scramjet, b) ejector scramjet with turbofan subsystem, and c) ejector scramjet with air liquifaction subsystem.

modes. At around $M = 12$–15 the engine is switched to the rocket-only mode (Fig. 3d). The air inlets are closed and the rocket is restarted, providing thrust to take the spacecraft into orbit.

System Studies

A system study in the mid-1960s was conducted to evaluate 36 different engines for a TSTO propulsion system.[7] Twelve of these, including RBCC engines, were identified as the most promising and received further evaluation. A U.S. Air Force study in the mid-1980s evaluated these 12 engines for SSTO propulsion systems and arrived at the five most promising ones.[6] These five engines consisted of the basic ejector scramjet (Fig. 4a) and four variants with one or more additional subsystems. Subsystems that the study indicated might be advantageously added to the basic ejector scramjet cycle are a turbofan to supercharge the flow in rocket-ejector mode (Fig. 4b), and an air liquefaction subsystem to produce the necessary oxidizer for the rocket in-flight in rocket-ejector mode (Fig. 4c). These engines were found to have overall mission-effective specific impulses between 630 and 780 s, compared with 370 s for a dual-fuel, all-rocket SSTO vehicle.[6] While adding capabilities to the engine, these subsystems also present additional design challenges for successful operation, which are discussed next.

In addition to the ejector scramjet cycle, the use of the ejector ramjet cycle, which does not employ a scramjet cycle between ramjet and rocket-only modes, is also being considered for ETO missions.[10] Several other vehicles with CCP systems have been analyzed, including both multiple-staged and single-staged vehicles.[11–16]

Review of Propulsion Research

Experimental

The initial work on RBCC engines had the goals of demonstrating the feasibility of the basic cycles identified by the system studies and showing that smooth mode transitions were possible. The results also began to quantify the performance that could be expected from these types of engines. Subsequent work has focused on performance increases through thrust enhancement and engine weight reduction. Much work has focused on rocket-ejector operation at flight speeds in the transonic regime, because this is the speed at which a vehicle experiences the maximum vehicle drag and minimum air capture.[17] Methods that have been suggested for reducing engine size and weight include mixing enhancement and the use of thermal choking to avoid the necessity of a variable geometry exit nozzle.

In the mid-1960s a series of experimental studies on combined-cycle engines were conducted. Several ejector ramjet test engines were constructed, including both hydrogen-[18] and hydrocarbon-fueled systems.[19] These engines were used for performance and thrust-minus-drag testing up to Mach 3 simulated flight conditions. The ejector ramjets utilized multiple primary rockets and featured both fixed and variable area flow paths. A smaller, axisymmetric, single-rocket hydrogen-fueled ejector scramjet test engine was also constructed.[20] It was operated over a wide range of conditions in rocket-ejector, ramjet, and scramjet modes using a single fixed geometry exit. Smooth transitions between modes were successfully demonstrated. Controlled thermal choking was achieved, demonstrating that thermal choking could be used over a wide speed range to control the location of the inlet shock in both rocket-ejector and ramjet modes. A schematic of this ejector scramjet engine test setup is shown in Fig. 5. The engine hardware of the ejector scramjet consisted of an inlet, primary combustor, constant area mixing section, slightly divergent combustor, and a more divergent nozzle. An H_2–O_2 rocket was placed on the engine axis inside the inlet spike. Wall-mounted fuel injectors were located at several axial locations along the combustor. A mixer-duct length-to-diameter ratio of 10 was used for complete mixing in the rocket-ejector mode. For the ejector ramjet and ejector scramjet, both specific impulse and thrust in the rocket-ejector mode increased with increasing Mach number (Fig. 1). Specific impulse augmentation of over 250% as compared with rocket-only operation has been reported.[21]

Recently, an ejector scramjet engine consisting of several struts in an engine duct was built.[22] Each strut houses four rocket nozzles and chambers and 10 fuel injector ports. Aerodynamically, the strut performs the functions of compressing the incoming air and isolating the combustor from the inlet. Studies have predicted the mission-integrated specific impulse to be 585 s for an SSTO, and 750 s for a TSTO vehicle using this propulsion system. The engine length is relatively short because the mixing of the fuel-rich rocket exhaust and incoming air in the rocket-ejector mode, and because of the fuel and air in the airbreathing modes is enhanced by the large number of rockets and fuel injectors. Testing performed on this engine configuration in ramjet and scramjet modes showed that combustion efficiencies as high as 95% could be obtained in relatively short engine ducts.[22]

Another experimental effort focused on the rocket-ejector mode operation of an axisymmetric engine configuration.[9] Thermal choking was demonstrated, and detailed measure-

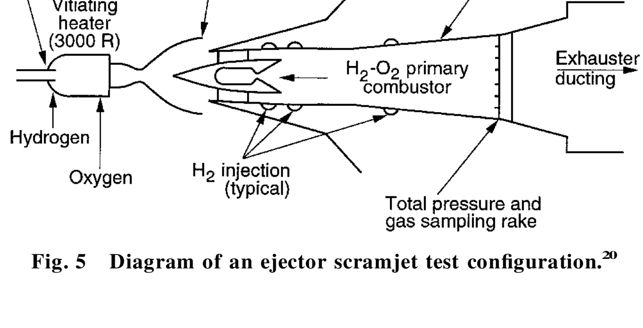

Fig. 5 Diagram of an ejector scramjet test configuration.[20]

ments of specific impulse, pressure rise in the ejector, and secondary air entrainment have been reported.

Large bodies of work exist on individual operational modes (ejector, ramjet, scramjet, and rocket) outside of the context of combined-cycle engines, but a review of these is beyond the scope of this work.

Modeling

A limited amount of analytical work has been performed on RBCC engines. Several one-dimensional modeling efforts have been reported.[9,23] A one-dimensional analysis was performed for an ejector scramjet-type configuration with a continuously diverging duct.[17] The rocket was assumed to operate fuel-rich, with the excess fuel reacting with the secondary air to add heat during the mixing process. The effects of the secondary-air Mach number at the rocket exit plane, a physical as compared to a thermal throat, bypass ratio, and equivalence ratio of the rocket were analyzed.

An early modeling effort used a mixing-layer solution method to predict the mixer flow in ejector ramjets and scramjets.[24] The mixing and thermal choking phenomena in a fixed-geometry diverging ejector scramjet engine operating in a rocket-ejector mode has been computationally modeled using an axisymmetric Navier–Stokes code with turbulence and finite rate chemistry.[25–27] A specific impulse of 640 s for the rocket-ejector mode with afterburning at a freestream Mach number of 0.8 was calculated, compared to a specific impulse of 340 s for the rocket alone.[26] A computational fluid dynamics analysis of a rocket-only mode was reported that explored the effect of different geometric parameters on specific impulse.[28]

General Combined-Cycle Propulsion Technical Issues

Airframe/Propulsion System Integration and Selection

Because of the high-speed airbreathing operation of CCP systems, a high degree of integration between the airframe and the propulsion system will be required. This is an issue that must be addressed in the design and optimization of any CCP system.[29] For example, combustion efficiency in the engine depends on the efficiency of the air capture by the forebody/inlet, and the aftbody partially serves as a nozzle.[30] Designs that are currently being considered include a very highly aerodynamic "flat" airframe and a highly axisymmetric vehicle design.[10] The choice of airframe will affect the engine design.

It is evident that the proper selection of engines for combined-cycle operation will be dictated by the mission requirements (hypersonic missile, SSTO accelerator, etc.). A transition between operating-mode cycles is typically accomplished when the effective specific impulse of the current operating mode falls below that of the next mode available in the multimode sequence, but it will also be dependent on the mission and vehicle design. For example, switching from scramjet to rocket-only modes at Mach numbers below 10 can significantly reduce the thermal loading on the vehicle.[31] Preferred vehicle takeoff and landing design choices are closely related to the selection of the propulsion system in the mission context. A review of the merits of alternative trajectories according to the selected propulsion system is given by Escher,[32] outlining certain advantages of horizontal-takeoff—horizontal-landing and vertical alternatives, i.e., vertical-takeoff–horizontal-landing or vertical-takeoff–vertical-landing.

Flow Path Design and Optimization

The advantage of being able to operate in several different cycles in a single engine carries with it the additional requirement of designing a flow path that will provide acceptable performance in each operational mode. The inlet will need to operate with a very low contraction in the rocket-ejector mode to capture as much air as possible.[17] However, in the scramjet mode it will need to have a large enough contraction to provide sufficient compression of the incoming air before combustion. The optimum exit flow path in rocket-ejector and ramjet modes includes a converging–diverging section, while scramjet mode requires straight and diverging sections only. Variable geometry, while an obvious solution, would add significant weight and complexity to the engine.[33] Fixed geometry flow paths are possible through the use of thermal compression and thermal choking to provide an effect analogous to area change in the flow path. Tailoring the fuel injection location and amount is used to alter the flow instead of variable geometry, and requires careful design of the fuel injection system. Fixed geometry inlets using thermal compression were proposed by Ferri,[34] and significant performance enhancement was shown to be possible at low hypersonic speeds.[35] However, progress on these concepts has been limited by the difficulty involved in tailoring the flow, fuel injection, and heat release.[4] For a fixed geometry combustor/nozzle, the flow path would also need to be optimized to allow controllable thermal choking in rocket-ejector and ramjet modes while avoiding thermal choking in scramjet mode.

Fuel Selection and Densification

The issue of fuel system selection is an important integrating factor in the development of high-speed propulsion systems, including combined-cycle approaches. It encompasses issues of fuel management, stability, and energy density, along with the need for fast breakup and chemical decomposition of the injected fuel. Often these requirements are in contradiction, because high energy-density fuels require high activation energies to initiate exothermic reactions.[36]

For SSTO vehicles, hydrogen provides an overall specific impulse better than hydrocarbon-based fuels because of the higher energy density (Fig. 1), and provides a source for active cooling of the airframe. In addition, the fast chemical kinetics of hydrogen are advantageous in reducing the combustion time in a scramjet mode. Advances such as gelled hydrogen[37] or slush hydrogen[38] provide methods to increase the density of hydrogen. Slush hydrogen yields a 15% increase in density compared to liquid hydrogen. In addition, it provides 20% greater thermal sink. This is important, particularly in the liquid-air cycle engine (LACE) concept where hydrogen "recycling," returning some hydrogen to the slush hydrogen tank for recooling, can increase the engine performance.

For TSTO vehicles, the use of hydrocarbon-based fuels, including new synthetic fuels, is a possibility. Hydrocarbon fuels require smaller tanks than hydrogen, reducing vehicle size and weight. A number of synthetic fuels have been developed recently that have the potential of an increased gravimetric energy output; hence improving the vehicle mass properties. This category includes energetic fuels, including strained-bond molecules and hydrocarbons with large molecular formulations or those including azido groups, as well as solutions of more traditional formulations with energetic additives. Aspects of the combustion characteristics of several such energetic fuels have been reviewed.[36,39,40]

Some newly synthesized hydrocarbon compounds with high energy density are very stable at normal conditions and could become practical storable fuels or additives for existing fuel systems. Because the newly synthesized hydrocarbon fuels often owe their high energy content to densely packed molecular structures, many of these formulations are solids under normal conditions and others are high-density liquids. For example, methylated polycyclic undane dimer (MPCU) is a compact hydrocarbon with a large molecular structure, $C_{22}H_{28}$, and a density between 1.2 and 1.3 g/cm^3, depending on the relative concentration of the isomers in the mixture, and a boiling point of around 80°C.[39] It has been shown that MPCU forms stable solutions up to 18% in kerosene, contributing to the increased energy density of the base formulation.[41] Experiments with droplet combustion showed that preferential boiling occurs because of the large difference in the vapor pressure in the binary solution, resulting in an effervescent combustion that accelerates the droplet burning rate.[41] In addition, the increased heat release from the combustion of the more energetic compound, such as MPCU, further accelerates droplet disintegration and combustion. While energetic materials show promise of increasing the volumetric energy content of overall propulsion systems, much analysis is still required to determine important characteristics of these materials, including vaporization, energetic output, and particulate formation.

Mode-Specific RBCC Technical Issues

Rocket-Ejector Mode

Mixing Enhancement

For rocket-ejector configurations in which a single circular cross-sectional centerline-mounted rocket is used, mixing lengths are large. Empirical correlations for this configuration indicate that a duct length-to-diameter ratio (L/D) of 8 to 10 is required for complete mixing,[20] and recent experimental results indicate complete mixing with $L/D = 8.5$.[9] Decreasing the duct length is important for reducing the weight of engines; however, mixing must be complete for efficient ejector operation. For these reasons, mixing enhancement is important in improving the performance of RBCC engines.

Increasing the interfacial shear area between the primary and secondary flows will increase the mixing action in terms of required length because mixing results primarily from the turbulent and viscous shear forces in steady flow ejectors. Using more, smaller primary rockets has proven effective in reducing mixing length.[19,22,42] The annular bell rocket, which has a toroidal combustion chamber and an annular nozzle, also increases the shear area.[43] An ejector utilizing an annular bell rocket mixes about four times as fast, lengthwise, as an ejector with an on-axis primary jet.[26] It has been estimated that a dual concentric annular bell would have an L/D of about one for complete mixing.

Another way to enhance mixing is by inducing large-scale motion between the primary and secondary streams, which effectively increases the shear area. Forced mixer lobes[44] and primary jets with noncircular cross sections[45,46] induce large-scale fluid motion through vortex formation. For highly elliptic-shaped jets, the entrainment of secondary fluid on the minor axis is increased by as much as a factor of 8 compared to a circular jet. The mixing rate on the major axis is about the same as that of a circular jet.[45] A large-scale swirl-type motion has been used to enhance mixing in a ramrocket, where the combustion air is introduced from the side of the mixing chamber in an otherwise coaxial flow.[47]

Turbulent mixing, which occurs in steady-flow ejectors, increases the stagnation pressure losses in the flow and results in lower performance compared with theoretical ideal mixing.[48] In contrast, dynamic ejectors rely primarily on unsteady pressure waves to accelerate the secondary flow and accomplish the momentum transfer and can, therefore, perform better than steady-flow ejectors. For example, an intermittent jet ejector, where the primary jet is pulsed, resulted in 90% thrust augmentation as compared to 30% augmentation for the corresponding steady-flow ejector.[49] Resonant acoustic modes excited naturally by the primary jet in some ejectors are correlated with increased mass entrainment.[50] In a rotary jet, the primary jets emanating from a freely rotating cylindrical or annular rotor drive the secondary air through the engine.[51] In a duct containing a planar rocket, switching the rocket exhaust flow from side to side causes increased acceleration of the slower secondary air.[52] Computational results indicate an increase of over 30% in specific impulse and a mass entrainment increase of over 10% at a switching frequency of 500 Hz compared to a steady-flow ejector.[53] Although dynamic ejectors may prove useful in combined-cycle engines, practical technical issues such as increased weight, induced vibrations, and achieving jet switching must be resolved.

Simultaneous Mixing and Combustion vs Diffusion and Afterburning

Related to the issue of enhanced mixing is that of whether to employ diffusion and afterburning or simultaneous mixing and combustion for the afterburning in the rocket-ejector mode. In the simultaneous mixing and combustion (SMC) approach, fuel-rich rocket exhaust is used to drive the mixer flow, and combustion is allowed to occur simultaneously with mixing and expansion. The resulting subsonic flow stream is then passed through a converging–diverging nozzle and expanded to supersonic velocities. An alternative approach is to mix a stoichiometric supersonic rocket drive jet with the subsonic inlet airstream and expand the combined subsonic flowstream to increase the static pressure. At the peak pressure point, additional fuel is introduced and combusted, and the entire flow is expanded through a converging–diverging nozzle. This approach is referred to as "diffusion and afterburning" (DAB). The SMC cycle exhibits consistently lower engine specific impulse at low Mach numbers relative to DAB cycles, as one would expect from basic thermodynamic consideration governing heat engine cycle efficiency. This difference is significant at sea-level static conditions but diminishes progressively with increasing Mach number.

One experimental study showed that combustion efficiency of the afterburner in the rocket-ejector mode decreased from over 90% with DAB to about 40% with SMC by decreasing the length available for mixing before fuel injection.[19] However, an SMC engine with a fuel-rich rocket exhaust has the advantage that separate downstream fuel injection capability is unnecessary, reducing the weight and complexity of the engine. It has been suggested that a shorter engine duct more than offsets the lower efficiency by a compensatory decrease in engine weight.[17] One suggested method to minimize losses is to introduce a fuel-rich flow that is shielded by the rocket exhaust from immediately mixing and reacting with the secondary air.[22] This eliminates the need for downstream fuel injection, while allowing the flow to more fully mix before afterburning occurs.

Enhancements to the Basic Ejector Scramjet Configuration

System studies indicated several subsystems could be added to the basic ejector scramjet to increase the specific impulse. One subsystem that improves the specific impulse in the rocket-ejector mode is a turbofan included in the flow path before the rocket (Fig. 4b).[6] A turbofan also adds the capability of powered loiter. However, these advantages come at the expense of increased installed weight and complexity. A major issue with this option is the removal of the rotating machinery from the flow path and stowage during elevated-Mach number flight to protect it from the extreme temperature conditions that would be experienced. Several methods have been suggested, including swinging or rotating the fan out of the flow path.[7]

Another method for increasing the specific impulse in a rocket-ejector mode at the expense of extra weight is to include a LACE subsystem (Fig. 4c), which implements an in-situ air liquefaction to provide the oxidizer for the rocket.[38,54] LACE systems have the advantage of further reducing the volume of stored oxidizer and, therefore, reducing the oxidizer tank size and weight. This type of engine collects and liquefies a portion of the incoming air in a heat exchanger which utilizes liquid hydrogen fuel in the condenser. Use of this subsystem would require a very compact, lightweight heat exchanger and a method for alleviating fouling and icing in the heat exchanger. In addition, more hydrogen is required to liquefy the air than is necessary for stoichiometric engine operation. This results in fuel-rich operation which substantially decreases specific impulse unless a thermal sink, such as slush hydrogen, is provided to recycle the excess fuel.

Thermal Choking in Rocket-Ejector and Ramjet Modes

One possible feature of ejector scramjet engines is a fixed geometry combustor/nozzle without a physical throat. As discussed earlier, this requires the use of heat addition to thermally choke the flow in the continuously diverging engine duct. In propulsion devices, a reduction in flow area is typically used to choke a flow. The fixed-diverging geometry exit in this engine configuration cannot contain a converging section because a decreasing area would tend to choke the supersonic flow in scramjet mode, which is unfeasible. Heat addition can be used to cause an effect analogous to a decreasing area, in that it drives the flow toward the sonic point. In rocket-ejector and ramjet modes, a fixed-exit geometry engine relies on thermal choking to obtain a flow that is subsonic in the mixer-afterburner yet supersonic in the nozzle, and to control and position the inlet shock. Further study is required to determine if the performance decrease of a thermally choked flow would be more than compensated by the reduced engine weight, as compared to a variable-area nozzle.[17]

The ejector scramjet test engine discussed earlier[20] achieved a thermal choke with subsonic combustion prior to the choke point in rocket-ejector and ramjet modes up to simulated flight Mach numbers of 5. The inlet shock location for supersonic flight speeds and the entrained air mass flow rate for subsonic flight conditions were controlled by varying the location of the fuel injection, which controlled the location of the heat addition to the flow and choke location. It has been shown computationally for an ejector scramjet configuration that an optimum afterburner combustor length exists. A combustor that is too long adds engine weight without a significant increase in performance. When the combustor is too short, a significant fraction of the combustion occurs in the more-divergent nozzle, which decreases the overall combustion efficiency and specific impulse and moves the choke point farther downstream in the nozzle.[25]

Flameholding in Scramjet Mode

The high-speed cycles in which supersonic combustion occurs raise particular difficulties because the chemical kinetics time scales are comparable with the short residence times of fuel in the combustor, about 1–2 ms. Difficulties include achieving sufficient mixing, high combustion efficiency, and flameholding. Issues related to fuel mixing and heat release in supersonic combustors have been reviewed in several studies.[27,41,55,56] For the high hypersonic range of interest for transatmospheric accelerators, above Mach 15, the short fuel residence times as well as use of the fuel to meet cooling requirements point toward a hydrogen-based cycle.[57] A detailed analysis of a hydrogen-based system is given by Billig.[15] Hydrocarbon fuels, which could be an option for TSTO vehicles, have the disadvantage of longer residence times to achieve vaporization, mixing, and combustion as compared with hydrogen. This makes the flameholding issue more critical for these fuels.

Flameholding is one of the key issues for high-speed combustion and it depends on a number of factors: the air velocity, ambient temperature, and the temperature of the fuel; the shape and size of the recirculation region devised for flameholding; the development of the shear layers at the air-fuel boundary that are responsible for mixing, hence combustion and heat release; and the fuel being used.

Ozawa's[58] generic study of flameholding of premixed, subsonic gases showed that the lean and rich limits of flame stability behind a flameholding body depend on the factors listed in the preceding text, which he combined in a generic stability parameter. However, flameholding of nonpremixed supersonic flows is substantially different from the premixed subsonic case and depends largely on the development of shear layers at the fuel/air boundaries. Furthermore, flameholding of nonpremixed gases are injection-geometry dependent and, therefore, more difficult to cast in a generic stability parameter (for a recent flameholding study in supersonic flows, see Ref. 59.) Some methods for flameholding that have been studied include using a pilot flame to increase temperature and provide a source of free radicals[60] and the use of a wall cavity to create a recirculation zone.[61]

One possible synergistic benefit of RBCC systems is in providing a source for flameholding in the high-speed airbreathing cycles. The rocket subsystem can provide a source of high-temperature, low-density gases, which accelerate the development of shear layers.[62] In addition, it would supply free radicals that accelerate the chemical kinetics. It could also act as a fuel injector by operating fuel-rich.

Rocket-Only Mode Cycle Efficiency

RBCC systems can make use of the airbreathing duct to act as a high-expansion nozzle when the ambient pressure is low to increase performance. This rocket-only mode of operation will need to be considered when optimizing the engine flow path because a well-designed ramjet or scramjet flow path will not necessarily result in high efficiency in the rocket-only mode. A recent modeling study investigated the effect of various parameters, including the engine duct area at the rocket exit plane, rocket nozzle exit area, wall angle, and base bleed, on the cycle efficiency of an RBCC engine in rocket-only mode operation.[28] Results showed that a large engine duct area at the rocket exit plane and a long engine duct decreased specific impulse, while large rocket nozzle exit areas and engine duct exit areas increased specific impulse. In addition, for a divergent nozzle, base bleed reduced the specific impulse. Depending on the geometry, cycle efficiencies ranged from about 78 to 95% of ideal rocket performance, which was computed assuming a well-designed nozzle with the same overall expansion ratio.

Discussion

RBCC engines were identified over three decades ago as a possible means to significantly increase the mission-average specific impulse for ETO missions. With current goals of an order of magnitude decrease in cost of payload to orbit, RBCC propulsion is becoming recognized as a promising technology for achieving this goal. There is a general consensus that these engines will play a significant role in the future of liquid propulsion. RBCC is also the leading candidate propulsion system in NASA's Highly Reusable Space Transportation initiative[10] and will likely power the X-37 vehicle. Most of the component and subsystem technology is in place for developing these engines; the main issues remaining are primarily those of integration.[63]

Summary

CCP systems that include rocket subsystems hold the promise of providing an increased mission-averaged specific impulse for transatmospheric flight compared to all-rocket systems. The operating cycles, which include rocket-ejector, ramjet, scramjet, and rocket-only modes, can provide takeoff capabilities, acceleration to hypersonic speed, and insertion into orbit. Synergistic interactions occur when rocket subsystems are integrated with airbreathing systems. These include a significant increase in the specific impulse in rocket-ejector mode compared to all-rocket specific impulse, possible use of the rocket for fuel injection and mixing enhancement in ramjet and scramjet modes, and the availability of the engine duct to operate as a highly expanded nozzle in rocket-only mode. Major issues of relevance for the development of such propulsion systems have been discussed. These include the following.

1) Engine/vehicle selection and integration: As with other high-speed airbreathing vehicles, a high degree of integration is required between the vehicle and the engine. Vehicle and engine choice and optimization will be interdependent.

2) Flow-path design for multimode operation: A CCP system benefits from the integration of multiple propulsion cycles in

a single duct, but design of that duct depends on all modes of operation. Design optimization will be required, and performance compromises will likely be required in every mode.

3) Fuel selection: Hydrogen will likely be the fuel of choice for SSTO applications, but TSTO vehicles could advantageously use a hydrocarbon-based fuel. Fuel densification could decrease vehicle weight and volume. This could be accomplished through slush or gelled hydrogen or, for hydrocarbon-fueled engines, through synthetic fuels or fuel additives.

4) Mixing enhancement: Significant increases in the specific impulse of RBCC engines can be obtained in the rocket-ejector mode because the rocket thrust is augmented by entraining and accelerating ambient air. Improved rocket-exhaust/air mixing to shorten the length of the engine, with the advantages of reducing the engine size, weight, and cooling loading, can be achieved by a number of methods. These include distribution of the rocket motors in several individual thrust chamber units, an annular rocket design, noncircular rocket exhaust ducts, or unsteady ejector operation.

5) SMC vs DAB: The afterburning in the rocket-ejector mode provides a significant increase in thrust and could be achieved by either simultaneous mixing and combustion or diffusion and afterburning. DAB yields increased combustion efficiency, while SMC could result in a smaller engine size and weight.

6) Addition of subsystems to the ejector scramjet: Adding turbofan or air liquefaction subsystems to the basic ejector scramjet increases rocket-ejector mode specific impulse, but also increases the weight and complexity of the engine. The use of these subsystems will likely be dependent on vehicle design and mission requirements.

7) Thermal choking: Thermal choking in rocket-ejector and ramjet mode operation of RBCC engines shows potential for mechanical simplification and weight reduction by allowing the use of fixed geometry flow paths and is an important issue for optimization of practical devices.

8) Flameholding: Operationally, a scramjet engine has yet to be developed. Flameholding is a key issue to be resolved for supersonic-combustion mode success. Synergistic benefits from the use of the rocket subsystem in an RBCC engine, including mixing enhancement and free radical injection, could be a significant benefit to scramjet-mode operation.

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