A Numerical Study of Hypersonic Fuel Injectors

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Abstract

The work conducted during the Summer of 1995 for the Langley Aerospace Research Summer Scholars, or LARSS, Program was a continuation of Master's Degree work being conducted for the Mechanical Engineering Department at Old Dominion University. Since this work is not yet complete, an update of progress is provided here along with a generalized background. The main emphasis of this research is to find predicted correlations in the database generated by the SHIP3D code, which modeled different scramjet combustor configurations.

Introduction

The next step in the evolution of aerospace propulsion is the bridging of the gap between today's high performance jet engines, known as ramjets (Mach 3-6), and rockets (Mach 25 +). The engine which fills this gap is the supersonic combustion ramjet. Ramjets are essentially self-propelling engines except that they need to be brought to an initial speed of approximately Mach 2.0 before they can operate. This engine is comprised of an inlet, a subsonic diffuser, a combustion section, and an exit nozzle. Air entering the engine is initially slowed in the inlet causing its static pressure to increase by use of oblique shocks. The air then passes through the subsonic diffuser where it is compressed further. This compressed air is subsequently heated in the combustor and then expanded through the exit nozzle at a velocity exceeding the inlet velocity. This increase in the speed of the working fluid is what provides thrust in the direction of flight. Ramjets require the velocity of the incoming air to be decreased in the supersonic and subsonic diffusers in order to prevent the combustor flame from blowing out.

At speeds greater than Mach 6, ramjets become inefficient due to the incoming air being slowed down to subsonic speeds. These inefficiencies manifest themselves as pressures too high for the combustor structure, excessive wall heat transfer rates, high total pressure losses from strong shocks, and energy losses to chemical dissociation [1]. To overcome these limitations, it is desired to induce combustion while the engine internal velocities are supersonic. Hence the need for a supersonic combustion ramjet, or scramjet. In order to bridge the gap between ramjets and rockets, it is desired that vehicles propelled by scramjets are able to obtain orbital velocity (≈Mach 25). Studies have shown that in order to propel a vehicle to Mach 25, internal flowrates through the scramjet will need to be between Mach 2 and Mach 8 [2].

When low earth orbit is desired, hypersonic airbreathing propulsion (Mach 5+) is an economically viable alternative to rocket propelled vehicles. The table below shows a takeoff weight breakdown of a typical aircraft and a conventional rocket launcher.

Typical takeoff weight breakdowns. From Heiser et al.[3] p.16

Takeoff Weight Fraction	Aircraft	Rocket
Payload	15 %	4 %
Empty	55 %	7 %
Fuel	30 %	24 %
Oxygen	0 %	65 %

Note that the largest fraction of a rocket's takeoff weight is oxygen and that this large investment of weight takes away from the vehicle's empty and payload weights. It is important to note that 'empty weight' includes items such as life-support, fuel tanks, power, controls, and engines.

A hypersonic airbreathing vehicle, on the other hand, acquires it's oxygen from the medium through which it traverses. This allows more takeoff weight to be invested in the payload as well as the vehicle empty weight. It has been proposed to reduce the fuel weight by using cryogenic hydrogen as the fuel, thus allowing for further reduction in takeoff weight as well as providing vital cooling potential for the internal engine components. Another important advantage to using hypersonic airbreathing vehicles based upon conventional aircraft design is the ability to use existing conventional runways, thereby not requiring any special launch facilities.

In order to obtain escape velocity, an airbreathing hypersonic vehicle will have to spend a majority of its acceleration time under power of scramjets. Therefore, the design optimization of this engine system is of greatest importance. The key to this optimization is the efficiency with which the fuel is mixed with the air passing through the engine. Work is currently underway at NASA Langley Research Center in Hampton, VA on the theoretical, as well as experimental, development of fuel mixing in scramjet engines.

Due to the cost of physical experimentation for these high-speed conditions, computational modeling is an attractive option. The use of Computational Fluid Dynamics (CFD) has been a great boon to hypersonic research. One code used to model the three dimensional physical processes inside a scramjet combustor is the Supersonic Hydrogen Injection Program, or SHIP3D. This code uses a four species combustion model in conjunction with the parabolized, mass-averaged equations for the conservation of mass, momentum, total energy, total fuel, and turbulence fields. The governing algorithm is the SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm created by Patankar and Spalding. For a more in depth discussion of SIMPLE the reader should refer to reference 4. SHIP3D was run modeling three different types of fuel injector (ramp, flush wall, and strut) with various parameters (i.e., fuel/air ratio, combustor length, injection angle, etc.) being changed. The objective of this Master's thesis is to look at various physical processes occurring around the injectors themselves and create a computationally derived database of these processes.

Summary

The following is a summary of work done as of August 8, 1995.

At the present time, a complete and thorough literature search is underway as well as developing plots of mixing efficiency vs. combustor length. Upon receiving the output from one of the flush wall injector cases, as well as a copy of SHIP3D, the first task was to see what the total stagnation enthalpy, total pressure, and the temperature were doing as the flow progressed through the computational combustor. After determining that mass conservation was being maintained by the code, it was desired to see what the individual species stagnation enthalpies were doing. This had a two fold effect. It allowed for a microscopic understanding of the combustion reactions taking place, but more importantly, it allowed for an in depth understanding of just what exactly the code is calculating and how it is calculating it.

One of the biggest difficulties in this project has been figuring out just how SHIP3D computationally recreates the various physical processes occurring within the combustor. This code has been modified for well over 15 years and was called HISS (**H**ydrogen **I**njection of a **S**upersonic **S**tream) as far back as 1977. Due to the years of modification by numerous individuals, as well as a lack of a concise cataloging document listing these changes, it has become difficult to have questions concerning the inner workings of the code answered quickly. This has led to a heavy investment of time in deciphering just how SHIP3D operates.

After determining the stagnation enthalpies for the individual species, it was decided to look at the pressure and viscous drags across the fuel injector. This was when some problems began to arise. In order to determine the pressure drag across the injector itself, the code had to be rerun so that the output would contain information for the desired locations in the combustor. After rerunning the code, it was found that the momentum losses were not adding up to equal the change in integral stream thrust. This is currently assumed to be due to mass loss inherent in the code itself as a result of the grid patching[5]. It was also found that when the code was rerun, the values for pressure drag began to diverge from previously calculated values (i.e., the database currently under study). The reasons for this have yet to be determined. It was assumed that the same input file was being used as in previous runs, so in order to maintain any consistency, the previously calculated values are going to be assumed to be the correct values.

Bibiliography

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