Introduction

"God could cause us considerable embarrassment by revealing all the secrets of nature to us: we should not know what to do for sheer apathy and boredom."
- Goethe (Johann Wolfgang)

The overall goal of any aerospace propulsion engine is the efficient production of net positive thrust, and careful development of the engine combustor can create significant gains towards this purpose. Subsonic combustion engines, such as ramjets, are limited to an upper flight speed of Mach 5 by the large total temperature rise associated with the deceleration of flow into the combustor inlet. The use of supersonic combustion reduces this total temperature rise, allowing higher flight velocities. However, with the use of supersonic combustion, new difficulties arise with effective mixing, cooling requirements, and various losses due to shock waves and wall friction. The development of a practical supersonic combustor design usually involves some tradeoff, one that balances the mixing and combustion characteristics with the pressure losses induced to achieve such conditions. Successful ignition and flameholding by the use of a plasma torch in a supersonic cross flow has been well documented. In addition, the enhanced mixing effects for fuel injected into a supersonic stream through multiple wall injectors arranged to produce streamwise vortices have been shown. The present investigation was designed to explore the fundamentals of plasma torch ignition enhancement, to investigate the combination of an aeroramp injector with a plasma torch, and to search for possible synergistic effects of the combination.

Plasma igniters have long been recognized as excellent sources of ignition enhancement for high-speed flows, but often without regard to optimization of the igniter performance, or the need for parallel design with a fuel injector. With an integrated plasma torch/fuel injector design, great benefits can be realized for supersonic combustion applications. This work focuses mainly on the efforts made to optimize the ignition performance of a low-power plasma torch, with the eventual goal of integrating it into an aeroramp fuel injector array. Experiments were conducted to determine the effects of ignitor power, feedstock type, and feedstock flowrate on torch performance. The results and design process of the integrated design are also presented.

The integration of a fuel injector and plasma torch is critical to assure good performance of the injection/ignition system. Although current supersonic flameholding methods have been demonstrated, many of these incorporate the use of bluff bodies such as ramps and cavities to provide the necessary subsonic regions for flameholding and pay little attention to the role of the igniter beyond that of a black box. The performance of these designs comes at the expense of the pressure losses induced by these physical shapes, which may not be necessary if subsonic flameholding regions can be provided by a flush-walled injector array. However, the real question to ask in these cases is, “Have the ignition system and fuel injection system been designed to work together?” Unfortunately, the answer is usually “no.” It has often been demonstrated that plasma torches have great potential to solve many of the problems associated with supersonic combustion, but unfortunately may not be realized due to a common lack of attention paid to the synergy that an integrated design would possess.

Goals and Objectives

The goals of the project is to provide fundamental insights on the synergistic combination of a plasma igniter and aeroramp injector, and to collect the data necessary for the successful development of integrated injector/igniter designs that perform better than current methods of supersonic flameholding. The following plan was followed to investigate the phenomena associated with such devices.

- Expand the understanding of how the plasma torch operates in an ambient environment.
- Apply this understanding to operation in a supersonic environment
- Develop a fuel injector that is compatible with the plasma torch
- Integrate the plasma torch and fuel injector
- Evaluate the performance of the integrated design using spectroscopy, total temperature sampling, and a number of supporting qualitative means.

Experimental Methods

The investigation and development of an integrated igniter/injector design for supersonic combustion applications has many steps, but only the key ones are discussed here. These steps were followed in producing the integrated plasma torch/fuel injector design presented within this report. First, a fundamental understanding of the plasma torch characteristics must be gained in a quiescent environment. To accomplish this goal, the effects of power, feedstock type, and feedstock flowrate on the distribution of combustion enhancing radicals in the plasma jet were measured spectroscopically. Second, the plasma torch was tested in a Mach 2.4 crossflow, similar to what it would experience in a supersonic combustor. The spectroscopic results were compared with the ambient tests to determine if the torch was operating as expected. Additional variables were studied, such as the angle of injection and the geometry of the anode nozzle, to determine their effect on the production and penetration of combustion-enhancing radicals.

Parallel to the investigation of the plasma torch, the fuel injector was optimized for mixing performance and studied to determine where the most suitable location for the plasma torch would be. A primary consideration in determining this location was to locate where the flammability limits existed for the particular fuel being injected. However, consideration of the plasma torch feedstock and feedstock flowrate were also investigated since the use of air or hydrocarbon plasmas would certainly affect the location of the flammability limits. Once an integrated design was selected, it was evaluated in a cold-flow tunnel.

Evaluation of the integrated design was mainly performed using spectroscopy to evaluate the distribution of radicals, total temperature sampling to evaluate the mixing characteristics. A variety of supporting qualitative methods such as filtered photography and oil-flow visualization were used as well to provide a more complete picture of the dynamics involved with such a device. Two questions were to be answered at this point: “Does the design perform as expected?” and more important, “is the integrated design better than the sum of its parts?” The second question implies that the characteristics of the plasma torch and fuel injector will actually work together, using their unique flow dynamics, such as vorticity and plume structures, to produce an effect that would be superior to the sum of either component working independently of the other.

Major Results

Throughout the work presented here, important discoveries were made assisting the development of the plasma torch as an igniter and its eventual integration into a fuel injector. Erosion studies of the anode demonstrated that molybdenum was a good substitute for tungsten, providing a long operational lifetime when tungsten anodes could not be used. In addition, the geometric studies of the torch anode revealed that the diverging section of the anode, traditional in many torch designs, was not necessary to protect the arc from the supersonic crossflow. This discovery allowed the complete removal of the diverging section, which essentially serves as a recombination region reducing the available energy of the plasma for ignition purposes. Evidence of the improved ignition characteristics was observed in an unheated Mach 2.4 crossflow by the presence of a flame plume. This flame plume was never observed before and is quite significant since the tunnel was unheated, with a static temperature of approximately 131 K. Furthermore, spectroscopic evaluation of the hydrocarbon plasmas showed that all the hydrocarbon feedstocks tested (methane, ethylene, propylene, and propane) produced similar spectrographs, indicating that each of the hydrocarbon plasmas contained the same excited molecular constituents. These radicals were shown to recombine or reach the ground state within 8 mm of the torch exit. Changes in torch power and feedstock flowrate over the ranges studied were shown to have very little effect on the propagation distance of these radicals, but rather, affected their local concentration near the torch exit.

Evaluation of the integrated design identified several important trends associated with the integration of a plasma torch and fuel injector. First, the aeroramp was observed to significantly improve the penetration height of the radicals produced by the plasma jet, but only for injector momentum flux ratios above 1.5. Also, increasing the torch power was observed to produce an exponential increase in the emission intensity of downstream products, indicating an increase in the reaction rate between the fuel and plasma. Total temperature measurements indicated that the thermal energy produced by the plasma torch was equally distributed between the right and left plumes produced by the aeroramp. Finally, the use of air as a torch feedstock produced highly luminous flame plumes at high powers. This was attributed to the presence of highly reactive atomic oxygen. Although these experiments were conducted in an unheated tunnel, the results demonstrate that the design holds potential and warrants further testing in a high-enthalpy tunnel for final validation.

Summary

The sections within this dissertation describe the results of multiple investigations of the ignition enhancement potential of plasma torches and the synergistic combination of a plasma torch igniter and aeroramp injector. The background, procedures, equipment and test results for each stage of the investigation are detailed. The analysis of the performance of the integrated design provides confidence that this design has great potential to be a reliable fuel injection and flameholding system for supersonic combustion applications.

The dissertation format outlines the important stages in the development of the plasma torch design and concludes with the studies of the integrated design. Chapters 2 and 3 provide background on the torch design and the experimental and equipment used in the tests. Chapters 4, 5, and 6 discuss preliminary studies necessary to understand how different anode materials are susceptible to various plasmas (Chapter 4), which radicals are present within various plasmas (Chapter 5), and how geometric changes of the anode affect the performance of the torch (Chapter 6). From these preliminary studies, a torch design was selected and tested in both a quiescent and supersonic environment, the results of which are presented in Chapter 7. In addition to the experimental work with the torch, a CFD analysis was performed to produce a computational model that could be used to predict the performance of the torch under various conditions (Chapter 8 and Appendix D). These torch-only studies were necessary to fully understand which aspects of the torch design are important for improving the ignition potential of such a device, in addition to gathering needed knowledge for future integration into the fuel injector. The results of the experiments performed with the integrated design are presented in Chapter 9, and conclusions are found in Chapter 10.