Chapter 10
Conclusions and Recommendations

Conclusion /nm./: the place where you got tired of thinking.

The goals of this research project were to investigate the fundamental processes associated with an uncooled, low-power plasma torch, and then apply that knowledge towards the development and investigation of an integrated igniter/injector configuration. The premise behind the work was that a flush-wall igniter/injection device could outperform existing systems in the areas of flameholding, mixing, and penetration, while producing equal or lower pressure losses. The scope of the work presented here focused on the investigation of important processes associated with the plasma igniter, and then on the integration of the igniter into a fuel injector array. Developmental stages of the torch dealt with the selection of an anode material, the anode geometry to maximize the ignition potential of the torch, and the evaluation of various hydrocarbon and inert feedstocks. Based upon these experiments, a torch was designed, built, and evaluated in both a quiescent and supersonic crossflow. To complement the experimental work, a CFD model was used to predict the performance of the torch under various operating conditions with methane. Parallel to this study was the development of the fuel injector array. After a fundamental understanding was developed of how the plasma torch and fuel injector worked as separate units, a preliminary integrated design was constructed and tested. The main results of the work are presented here.

Due to the complexity of the anode for the plasma torch used in these experiments, it was necessary to machine the anode out of a material other than tungsten, a traditional electrode material, but also extremely hard. Experimental work with copper, molybdenum, and tungsten-copper anodes was performed to find a suitable replacement for tungsten. The main results from this investigation were that:

- Molybdenum provides the best combination of material properties as a substitute for tungsten when used with hydrocarbon feedstocks.
- Molybdenum anode lifetimes are significantly longer than those for copper, or tungsten-copper anodes.

- When using air or nitrogen feedstocks, the plasma produced was highly erosive to molybdenum, and was found not to be as erosive to copper.
- The results from an analytical model of the arc diameter at the anode attachment point agree quite closely with those of the experiments.

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Geometric studies of the plasma torch anode focused on geometric aspects of the anode believed to hold potential for improving the ignition capability of the torch. Three geometric features were investigated: the torch injection angle, anode constrictor length, and the addition of various types of diverging nozzles at the end of the constrictor. New discoveries include:

- Angled injection was observed to both decrease the penetration height of thermal energy, measured through downstream total temperature sampling, and the spectral intensity of the jet, indicating a lower concentration of excited hydrogen atoms.
- Increasing the length of the anode constrictor increased the concentration of excited hydrogen atoms within the plasma jet but also introduced stability problems due to the extended arc length.
- The addition of a diverging nozzle was hoped to increase the penetration height of radicals, but erosion in the throat disrupted the nozzle flow so that the penetration characteristics of these designs were poor.
- Diverging nozzles were found to introduce recombination regions in which radicals recombine, essentially providing a volume that reduces the available energy for ignition before the plasma jet can interact with the main flow.

Spectrographic evaluation of the various hydrocarbon and inert plasmas was key in understanding what types of combustion enhancing radicals were present within the plasmas. Studies of methane, ethylene, propylene, propane, air, and nitrogen were performed to investigate the species contained within the plasmas produced by these feedstock gases. The spectrographic investigation of these feedstocks indicated that:

- Each of the hydrocarbon plasmas contained atomic hydrogen, H, a well-known combustion enhancing radical.
- Other identified hydrocarbon plasma species included C_2, C, H_2, CH, CN, CH_2, and NH.
- Heavier hydrocarbons exhibited increased rates of electrode erosion.
- Air and nitrogen plasmas contain excited atomic and diatomic air species. Of these, atomic nitrogen and oxygen were identified as the most important for combustion enhancement.

Based upon the knowledge gained in the geometric, anode material, and spectrographic studies, a standard plasma torch anode was designed. The performance of the torch was then evaluated extensively with methane and nitrogen, and to a lesser extent ethylene. These investigations identified important phenomena associated with plasma torches such as:

- Methane and ethylene flame plumes were produced in the cold, Mach 2.4 environment, due primarily to the removal of the anode nozzle in the geometric studies.
- Increases in torch power produced an increase in the bow shock angle, caused by volume addition effect through a rise in total temperature and a decrease in the molecular weight of the feedstock gas.
- The plasma jet was discovered to exhibit an arrowhead shape, rather than a perfect cone as previously thought.
- Tests with nitrogen in the Mach 2.4 crossflow produced plumes of excited NO, as predicted by the Zeldovich mechanism, and indicates the reaction of excited monatomic nitrogen with oxygen to produce NO and atomic oxygen.

A CFD model was developed in the hope of being able to predict the performance of the torch through computational means. The model incorporated a methane combustion mechanism coded into GASP®, a time-dependent Reynolds-averaged Navier-Stokes solver. Comparison of the CFD predictions to experimental results showed that:

- The CFD model accurately predicted the penetration height of the thermal energy imparted by the plasma jet, but failed to correctly model the shape of the downstream plume profile.
- Improvements to the model were made by incorporating a new grid structure and turbulence model. These changes improved the accuracy of the model when no combustion mechanism was included. This indicates that the use of a combustion mechanism to model charged plasma might not be necessary.

Using the knowledge gained from the torch investigations, the plasma torch was integrated into an aeroramp fuel injector array. The study of the phenomena associated with this type of integrated device produced several important trends that hold immediate relevance for supersonic combustion applications.

- The aeroramp injector was observed to significantly increase the penetration height of the radicals produced by the torch for injector momentum flux ratios above about 1.5.
- Increasing the torch power produced an exponential increase in the intensity of downstream products, indicating an increase in the reaction rate between the fuel fed through the injector and the plasma produced by the torch.
- Even mixing of the plasma jet thermal energy between the aeroramp plumes was observed through total temperature sampling. In supersonic combustor applications, this would translate into an even burning of fuel.
- At powers above 3000 W, air was observed to produce a highly luminous flame plume attributed to the production of atomic oxygen, indicating that under high-enthalpy conditions, air may hold the best ignition potential for this design.

The research presented here focused on increasing the knowledge base of the fundamental processes associated with a plasma torch for ignition enhancement and flameholding, the integration of the torch into a fuel injector array, and the phenomena associated with such devices. The integrated design is expected to exhibit superior performance to existing devices based upon the ability to flamehold, mixing, and penetration characteristics. The developmental process revealed key geometric and operational aspects that could be changed to improve the ignition potential of the plasma torch. The integrated design demonstrated a definite synergistic effect of the combination, resulting in a design that is greater than the sum of its parts. Experiments at Virginia Tech demonstrated that the design holds potential for use in supersonic combustion applications.

10.1: Recommendations

Based upon the knowledge gained in the research program presented here, the following recommendations are made regarding future research endeavors in this field.

- The use of air feedstocks in applications of this type holds great promise, and effort should be focused on the development of electrodes that are resistance to oxidation at high temperatures. This will increase the lifetime and usefulness of the torch when operating on air.
- Electrode particle emission may play a significant role in the field of combustion enhancement and should be investigated. These particles may be injected either through the use of a consumable cathode, or by means of seeding the flow with metal-oxide particles.
- Improvements to the presented CFD models should be explored, particularly regarding whether it is appropriate to use a combustion reaction mechanism to model a plasma jet.
- Geometric investigations of the plasma torch anode revealed that the ignition potential of the torch could be enhanced through geometric variations of the anode constrictor, injection angle, and nozzles. Future researchers may want to investigate changes in the constrictor shape, cathode design, or the addition of cooling to increase anode lifetime.

- Regarding the integrated design, experiments in a high-enthalpy tunnel would allow investigations of power and fuel flowrate ranges to be explored, yielding valuable insights on the operational limits of the design.