

A Study of Plasma Ignition Enhancement for Aeroramp Injectors in Supersonic Combustion Applications

by

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(ABSTRACT)

The main goal of this project was to investigate the mixing and chemical phenomena associated with the integration of a low-power, uncooled plasma torch into a fuel injector array. The potential application was for an integrated scramjet igniter/injector, with the hope of producing superior mixing and flameholding performance for supersonic combustion applications. To create a knowledge base for integration, several key investigations were made of the anode material, anode geometry, and spectrographic analysis of different light hydrocarbon fuels and inert feedstocks, all aimed at increasing the ignition potential of the plasma torch. Investigations of the anode material demonstrated the molybdenum provided longer lifetimes than either pure copper or tungsten-copper anodes. In addition, geometric studies of the anode revealed that anodes with short constrictor lengths and sonic exit nozzles provided superior ignition performance based on higher transfer rates of thermal energy from the arc to the feedstock. This resulted in the production of higher hydrogen atom concentrations within the plasma jet. Spectrographic observation of the plasma jets revealed that methane, ethylene, propylene, and propane plasmas all contain excited atomic hydrogen, a radical known to participate in important chain-branching combustion reactions.

Based on the knowledge gained, and encouraging results, a candidate scramjet igniter and flameholder was designed. The design was observed to exhibit a synergistic effect between the plasma igniter and fuel injector in that the fuel injector provides not only a subsonic region for plasma ignition, but also lifts the combustion enhancing radicals out into the fuel-air stream by means of counter-rotating vortices. Furthermore, under the conditions tested, increases in plasma torch power produced an exponential increase in the intensity of downstream products, indicating an enhancement effect. Based upon these observations, the integrated igniter/injector design is expected to perform well in supersonic combustion applications.

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Nomenclature

Symbols

A	A constant
A	Concentration of specie "A"
B	Concentration of specie "B"
C_p	Specific heat
d	Diameter
e	Electronic charge
E	Voltage gradient along an arc
E_A	Activation energy
H	Heat carried away through convection
h	Heat transfer coefficient, Planck's constant
I	Arc current
j	Current density
J_o	Nondimensional constant
k	Thermal conductivity
k_B	Boltzmann's constant
k_e	Conductivity at melting
L	Lorentz Ratio
M	Mach number
\dot{m}	Mass flow rate
N_{AV}	Avagadro's number
\dot{Q}	Rate of heat transfer
p	Pressure, Steric factor
P_t	Torch power
q	Jet to freestream momentum flux ratio
q_e	Heat transfer at the point of arc attachment
r	Radius of anode constrictor
R	Radius of bow shock
R_o	Characteristic radius of bow shock
R^2	Coefficient of variation
\dot{S}	Rate of entropy production
R_o	Characteristic radius of bow shock
R_u	Universal gas constant
t	Anode thickness
T	Temperature
v	Uniform velocity of a gas
V_{af}	Voltage across anode fall
V_i	Ionization potential
W	Molecular weight of a gas
x	Fraction of ionized atoms within a gas
x	Streamwise coordinate
y	Spanwise coordinate
z	Vertical coordinate

Greek Symbols

δ	Thickness of anode fall
ε	Effective ionization potential, A multiplication factor
ξ	A multiplication factor
γ	Ratio of specific heats
ϕ	Thermionic work function
ρ	Density
σ	Boltzmann Constant
σ_e	Electrical conductivity of a gas
σ_{AB}	Collision cross section
ν	Frequency of radiation

Subscripts

∞	Freestream
a	anode
e	electron
eff	Effective
eq	Equivalent
inj	injector
j	jet
o	total value
p	plasma
s	Sensible
t	torch, total value

Motivation

The benefit of using supersonic combustion over subsonic combustion in high-speed flight vehicles is the attainment of higher flight velocities and lower fuel-consumption. With the added challenge of supersonic combustion, new difficulties arise with effective mixing, ignition, and maintaining combustion. Furthermore, these difficulties are compounded through the use of hydrocarbon fuels, which, although they contain more energy per unit volume than hydrogen, are hard to ignite. The development of a practical supersonic combustor design usually involves some tradeoff between the mixing and combustion characteristics, and the necessary losses needed to achieve such conditions. Traditional methods of injection and flameholding usually incorporate a physical shape used to provide a subsonic recirculation region to which a flame can be anchored, at the cost of large pressure losses. In addition, ignition and injection schemes have been largely unintegrated, usually with the majority of the work focused on the injection mechanisms. A huge potential lies undiscovered, both in the possibility of using flush-wall injectors to reduce total pressure losses, and within the largely overlooked ignition system. The careful integration of these two key components could potentially realize huge benefits over current injection/flameholding schemes.

This investigation was planned to discover the fundamentals of hydrocarbon plasma jet operation and vortex-induced flush-wall injectors that would lead to a synergistic combination. The premise behind the integration of the two components is the thought that the end result would be an integrated design that achieves greater performance due to the careful study of a torch as an igniter, and the integration of the torch into a fuel injector, in essence, investigating the potential largely overlooked in conventional designs. The investigation of the torch focused on the fundamentals of torch performance as an igniter, i.e. what aspects of the torch can be changed to improve the ignition and flameholding characteristics of the torch? Based on the knowledge gained in these investigations, a preliminary igniter/injector design was built. Studies of the integrated design were aimed at investigating the synergy between the igniter and injector, and the mixing/flameholding phenomena associated with such a device.