A microwave-augmented plasma torch module as an igniter/fuel injector of a scramjet engine

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Abstract. A plasma torch designed to be an ignition aide/fuel injector within a supersonic-combustor is described. The desirable features include 1) a microwave adaptor arrangement to couple additional power (from microwave as well as arc discharge) to the plasma torch; 2) an additional port for fuel injection; and 3) compact (including the power supply), portable, and lightweight. In this device, a cylindrical-shaped plasma torch module is integrated into a tapered rectangular cavity to form a microwave adaptor that combines arc and microwave discharges to enhance the size and enthalpy of the plasma torch. A theoretical study of the microwave coupling from the cavity to the plasma torch, providing a guide of the design, is presented. The numerical results indicate that the microwave power coupling efficiency exceeds 80%. This torch system is operated in periodic (60-Hz) mode. The plasma jet generated by cyclical discharge is described by the cycle energy of the discharge and through imaging of its plume under various conditions, the supply air pressure and microwave (on or off) to the torch. The microwave electric field has a profound effect on the arc discharge. Operational tests of the device confirm that microwave power is effectively coupled to the plasma torch and enhances the arc discharge power. It intensifies the emission and increases the volume of the arc discharge region. It also enhances the electron temperature significantly as shown by the emission spectroscopy of the torch. The addition of microwave energy enhances the height, volume, and enthalpy of the plasma torch when the torch operates at low airflow rate, and noticeable microwave effect on the plasma torch can still be observed even when the flow speed is supersonic. Since the spatial distribution of the microwave electric field outside the nozzle of the torch module will not be affected by the supersonic cross flow, the added microwave is a favorable feature for increasing the penetration depth of torch plume into the supersonic crossflow in the combustor of a scramjet engine. In addition, this torch can be operated as a combined fuel injector and igniter. Ignition of ethylene fuel injected through the center of tungsten carbide tube acting as the central electrode is demonstrated.
1. Introduction

In the combustion of hydrocarbon fuels, e.g., cold liquid JP-7 fuel [1,2], fuel-air mixing is critical. The hydrogen and carbon in the fuel need oxygen in the air to complete the chemical reactions. The fuel-air mixture will not auto-ignite, even as the static temperature of Mach-2 airflow is increased to about 500 K. After being ignited, the reaction rate increases with the initial temperature of the mixture, which changes the ratios of the components in the composition of the mixture. At low temperature, the gas mixture contains mainly neutral molecules, and neutral-neutral reactions often immeasurably slow. For example, the rate coefficient for the reaction between H\(_2\) and O\(_2\) is 6×10\(^{-23}\) cm\(^3\)s\(^{-1}\). As temperature increases, some radicals such as atomic species are produced. Neutral-radical reactions have rates in the range of 10\(^{-16}\) to 10\(^{-11}\) cm\(^3\)s\(^{-1}\). For example, the reaction between H and O\(_2\) has a rate coefficient equal to 1×10\(^{-13}\) cm\(^3\)s\(^{-1}\). Reactions also occur between radicals, which in fact have higher rates in the range of 10\(^{-13}\) to 10\(^{-10}\) cm\(^3\)s\(^{-1}\). Hence, the combustion rate is increased as the percentage of radicals in the mixture becomes significant as the temperature increases [3,4]. The temperature of the mixture can be enhanced by several ways including preheating the airflow, adding energy via plasma torch, and
positive feedback from enhanced combustion, etc. If the temperature of the mixture is high enough to cause significant ionizations, the combustion rate is further enhanced [5]. This is because ion-neutral and ion-electron reactions have rates larger than $10^{-9}$ cm$^3$ s$^{-1}$ and $10^{-7}$ cm$^3$ s$^{-1}$, respectively. For instance, the reaction $\text{H}_2^+ + \text{O}_2$ has a rate coefficient of $8 \times 10^{-9}$ cm$^3$ s$^{-1}$. It turns out only long-range ion-electron and ion-dipole reactions are fast enough to react on supersonic flow time scales in the $\mu$s range. Therefore, it is desirable to preheat the mixture and also introduce ionized species to the mixture in a supersonic combustor.

The scramjet propulsion system [1,2,6] has a simple structure in its supersonic combustor, as required by the hypersonic aerodynamics. Basically, the combustor has the shape of a flat rectangular box with both sides open as seen in Fig. 1, which presents a schematic of a scramjet engine. Air in-taking through the frontal opening of the combustor mixes with fuel injected in through sidwall(s). After the combustion, the heated exhaust gas at the open end is ejected out through a nozzle to produce the engine thrust. However, the residence time of fuel through the combustion region is short, of order 1 ms. Within scramjet test facilities, the typical mechanisms for achieving the required downstream pressure rise (and stable combustion) are the so-called aero-throttle, where a “slug” of gas (air and silane) is injected in the downstream region, and the heat is released from the pyrophoric gas silane (SiH$_4$). Both of these approaches, however, have their disadvantages: for example, the aero-throttle approach may not allow re-lighting attempts and silane poses obvious safety risks (silane can autoignite in air). Moreover, the aero-throttle approach degrades the performance of the engine from that of a real scramjet [7]. Thus, an alternative approach, which can reduce the ignition delay time and increase the rate of combustion of hydrocarbon fuels, is desirable [8,9]. Detailed kinetics modeling [5] shows a significant decrease in ignition delay in the presence of initial ionization—in the form of a H$_3$O$^+/\text{NO}^+/e^-$ plasma—at degrees of ionization greater than $10^{-6}$. The ignition delay time is decreased most significantly at low temperatures. Indeed, the computational results suggest that even larger effects may be observed at the low temperatures encountered under engine startup.

A plasma torch placed right behind the fuel injector can replace silane for ignition purposes by delivering enough heat to ignite injected fuel [10-12]. Moreover, the high-temperature torch effluent includes quantities of radicals, ions, and electrons, which work to enhance the combustion rate. A significant decrease in the ignition delay time and the initial energy carried by a plasma torch may elevate the heat release from combustion to exceed a threshold level for downstream pressure rise. With sufficient downstream pressure rise, a shock front will propagate upstream of the region for helping combustion and flame propagation. The heat release from combustion will maintain the pre-combustion shock front. These are the primary reasons that plasma torches [10-15] are being developed for this application.

A high-pressure plasma torch can be produced through DC or low frequency capacitive [16,17] or high frequency inductive arc discharges [18], which require adding flowing gas to keep the discharges from arc constrictions. The gas flow also carries generated plasma out of the discharge region to form an extended plasma plume, thereby creating a torch. The inductive torch and non-transferred DC torch employ high current power supplies and require external cooling to achieve stable operation. Consequently, the structures of these torches are relatively large and are therefore unsuitable for the ignition application. The torch module patented by Kuo et al [19] can run in DC or low frequency AC mode and can produce high power (a few kW in 60-Hz periodic mode or hundreds of kW in pulsed mode) [20] plasma torches. It is compact and there is no need of external cooling in its operation. The size of the torch plume and the energy of the discharge increase as the gas flow rate increases. On the other hand, a large flow rate
decreases the average gas temperature, which is not beneficial for the ignition application. It is also noted that a thermal plasma torch is not sufficiently energy efficient to introduce enough ionized species to the fuel-air mixture.

Nonequilibrium plasmas produced by corona, streamer, pulsed glow and microwave discharges have also been suggested, as alternatives to the plasma torch, for aiding the ignition process. These discharges, run at high E/N, can potentially enhance dissociations in fuel and air by direct electron impact, where E is the electric field and N is the gas density. However, the practical concern is the combustion efficiency, rather than the energy efficiency of the igniter. The combustion efficiency depends not only on the chemical processes but also on the spatial distribution of the plasma energy, particularly for supersonic combustor. These alternatives as igniters can only start the ignition locally, for instance, near the wall; these approaches are not practical because a considerable percentage of injected fuel will not be ignited before exiting the combustor. In other words, a practical igniter is necessary to project the introduced thermal energy (e.g., carried by the super-thermal gas or nonequilibrium plasmas) into the engine in such a way that it readily mixes with a fuel-air stream. Poor penetration of the introduced thermal energy into the combustor, and/or improper placement of each igniter—that is, more than one igniter may be required—will limit its effectiveness.

Microwave power can be used to produce an electrodeless discharge resulting in relatively large volume plasma with no need to flow gas through the discharge. Usually, an arrangement to localize microwave discharge in a designated region away from the source is needed. Using a high Q cavity, a gas flow is used to blow the microwave plasma out of an exit hole on the cavity/waveguide wall to form a plasma torch for the application. However, the required Q-factor limits the size of the hole, which in turn limits the diameter of the torch. Moreover, cavity based microwave plasma torches are difficult to use as an igniter within a supersonic combustor. This difficulty results from the fact that the walls of the engine have a thickness of more than 50 mm, and large openings on the walls are forbidden in order to minimize the perturbation on the supersonic flow in the combustor. In addition as a practical matter, there are no large empty spaces adjacent to the walls for accommodating a microwave cavity. On the other hand, if an arc discharge is introduced, the microwave is added to assist the existing discharge, rather than to initiate a discharge. Then the applied microwave power can be effectively dissipated only in the discharge region, where a significant amount of seed charges exist.

In the present work, a microwave-augmented plasma torch is invented [21-23]. It combines an arc torch module with a rectangular microwave cavity in the form of a microwave adaptor. The torch module is used not only to generate the arc plasma but also to couple the microwave power from the cavity to the arc plasma for microwave enhancement. Most importantly, this torch module doesn’t require the microwave cavity to be adjacent to the engine walls; it can still be easily plugged to the engine along with a required seal to high-pressure gas; and the required opening on the engine wall is the same as that for a simple arc torch module. In Sec. II, the plasma torch module is described. A theoretical formulation and numerical analysis of the microwave coupling efficiency of this adaptor are presented in Sec. III. The experimental results demonstrating microwave effect on the physical size and enthalpy of this plasma torch are presented in Sec. IV and on the electric characteristics of the plasma torch are presented in Sec. V. In Sec. VI the emission spectroscopy of the torch is studied. The capabilities of the torch as an igniter and as a pre-ignited fuel injector of hydrocarbon fuel are demonstrated in Sec. VII. Finally, in Sec. VIII summary and conclusions are given.
2. Description of the Device

The components of this plasma torch device include 1) a 2.45 GHz, 1.5 kW magnetron as the microwave source, 2) an arc torch module, 3) a tapered microwave cavity, and 4) a power supply to run the torch module and the magnetron.

2.1. Arc torch module

The cylindrical arc torch module, which uses the frame of a cylindrical tube having an outer diameter of 16.5 mm as the grounded outer electrode, is first described. This torch module is similar to that developed by Kuo et al [19,20], with the exceptions that the device is longer and has an integrated gas plenum chamber allowing for the module to be integrated into a supersonic combustor. Moreover, the central electrode is replaced with a tungsten carbide tube providing an additional flow path for either air or fuel. The concentric electrodes in the module are separated at the nozzle exit location by a gap of 2.16 mm and insulated by a ceramic tube, having outer and inner diameters of 9.53 mm and 3.81 mm, respectively, and dielectric constant $\varepsilon_r = 8$, which hosts the central electrode. The frame, having a length of 146 mm, consists of three sections. The bottom section is 51 mm in length, having an inner diameter slightly larger than 9.53 mm to be tied fit with the ceramic insulator. It makes easy to center the central electrode hosted by the ceramic insulator. In the torch operation gas flow through the gap between electrodes is necessary. Thus the central section having a length of 93 mm is open up to a much large inner diameter of 12.7 mm so that this section functions as a gas plenum chamber. A threaded nozzle of 2 mm length is inserted at the top of the frame to increase the gas flow speed in the discharge region. This nozzle has an inner diameter of 7.5 mm. The ceramic insulator does not cover the central electrode in the nozzle. It is placed slightly below the bottom of the nozzle (this is because the ceramic insulator at high temperature is not a good insulator anymore). The central electrode is a tungsten carbide tube with inner and outer diameters of 1.14 mm and 3.18 mm, respectively, and fits tightly inside the ceramic insulator. The hollow center section can be connected to a separate gas supply allowing for an additional, independent flow path. For instance, it can be used for injection of ethylene fuel for fuel injection directly through the discharge region. However, any gas can be used in either the inner or outer flow paths. Fig. 1a is
a photo of disassembled arc torch module showing its components; in the photo the labels A = 16.5 mm, B = 2 mm, C = 93 mm, and D = 51 mm as described early, where D includes the height of the module holder welded on top of the cavity. A photo of assembled torch module is shown in Fig. 1b. The structures of the module in sections corresponding to C and D are similar to that of a coaxial line. These two sections have characteristic impedances of $47.4 \, \Omega$ and $24.5 \, \Omega$, respectively. The top part (labeled by B) connects to a plasma load, which varies with the temporal variation of discharge. The central electrode sticking out from the bottom of the frame is used to connect to the high voltage for arc discharge and to the fuel line as well as used as an antenna to couple microwave into the coaxial line and to the plasma load. This part of the central electrode is covered partially by the ceramic insulator.

2.2. **Tapered rectangular waveguide cavity**

An S-band rectangular waveguide having a cross section of $a \times b_0 (= 72 \, \text{mm} \times 34 \, \text{mm})$ is tapered to a cross section of $a \times b (= 72 \, \text{mm} \times 5 \, \text{mm})$. The two ends of the waveguide are terminated by conducting plates to form a rectangular cavity. This cavity consists of three sections. Two sections with uniform cross section are connected by a tapered section. The first section (cross section of $72 \, \text{mm} \times 34 \, \text{mm}$) has a length of $3\lambda_z/8$ and the last section (cross section of $72 \, \text{mm} \times 5 \, \text{mm}$) has a length of $\lambda_z/2$ where $\lambda_z = \lambda_0/[1 - (\lambda_0/2a)^2]^{1/2} = 233 \, \text{mm}$ is the axial wavelength for the TE$_{103}$ mode, $\lambda_0 = 122.5 \, \text{mm}$ is the free space wavelength, and $a = 72 \, \text{mm}$ is the dimension of the wider side of the cross section. The middle transition section, tapering the cross section from $72 \, \text{mm} \times 34 \, \text{mm}$ to $72 \, \text{mm} \times 5 \, \text{mm}$, has a length of $\lambda_z/2$ and a slope angle $\theta = 14^0$. This cavity is similar to the one used in a microwave torch device reported previously [24].

Microwave generated by a magnetron (2.45 GHz, 700 W to 1.5 kW) radiates into this cavity at a location of $\lambda_z/8$ distance away from the shorted-end of the non-tapered section of the cavity. The quarter wavelength in the axial direction of the uniform sections of the cavity is $58.3 \, \text{mm}$ and the wavelength in the middle transition section is expected to be a little shorter; thus, the total axial length of $320 \, \text{mm}$ matches the length requirement for the TE$_{103}$ cavity mode. This result was confirmed by a measurement of the spatial distribution of the microwave electric field normal to the bottom wall of the cavity (Fig. 2 in Kuo et al [24]).
In the narrow section of the cavity, two aligned holes on the bottom and top walls of the cavity at a distance $\lambda_c/8 = 29.2$ mm away from the end are introduced. The top hole has a diameter of 9.53 mm and a tube fitting is welded to it. The arc torch module shown in Fig. 1b is then installed through the holder, as shown in the photo of Fig. 2, by inserting the bottom part containing only the central electrode and the ceramic insulator of the torch module through these two aligned holes. The bottom hole on the cavity wall has the same diameter of 9.53 mm fitted exactly to the ceramic insulator. The portion of the central electrode of the torch module inside the cavity functions as a receiving antenna and the portion (~146 mm) of the torch module above the top wall of the cavity functions as an open-end transmission line. In this configuration, the plasma torch module becomes a microwave adaptor. In Fig. 2, a magnetron with its transmitting antenna inserted into the cavity from the other side (non-tapered section) is also shown. The insert in the photo is a top view of the arc-torch module, showing concentric electrodes separated by a ceramic insulator. The airflow blows out through the gap between the ceramic insulator and the outer electrode. The central electrode is a hollow tube. When plasma is generated by the arc discharge between the electrodes of the arc torch module, it introduces a time varying resistive load to the adaptor. The effectiveness of delivering microwave through this adaptor to a dynamic load will be analyzed and presented in the next section.

This new type arc/microwave hybrid plasma torch does not need gas flow in its operation and yet can produce a sizable plasma torch. However, introducing gas flow can increase the size as well as the energy of the plasma torch.

2.3. **Power supply**

The power supply consists of a high power transformer, diodes, and capacitors. Two sizes of transformers are used. The big one has a turns-ratio of 1:17; it uses a (60-Hz) single-phase 208 V power line for the input. The small one has a turns-ratio of 1:25 and uses (60-Hz) 120 V as the
input. This power supply initiates the arc discharge on the first cycle after power is applied to the transformer. However, a few seconds are required to heat-up the filament of the magnetron before the torch operates in a microwave-augmented mode.

Both the torch module and magnetron operate at the power line frequency, with less than 50% duty cycle. Hence, the synchronization of the two components in each cycle is essential to the operation of this hybrid torch module. The optimal operation condition is when the arc discharge pulse of the torch module and the microwave pulse of the magnetron overlap in time. The microwave field is too small to initiate discharge by itself for the microwave power used in the present setup. Since the discharge pulse is shorter than the microwave pulse, the arc discharge needs to start at the beginning of the steady-state level of the microwave pulse. Thus, the two components share the same power supply to simplify the synchronization.

Fig. 3 shows a circuit diagram of the power supply used in this study, which is capable of operating the arc discharge and the magnetron simultaneously. The big transformer with a turns ratio of 1:17 steps up the line voltage of 208 V (rms) to 3.5 kV (rms), which is applied to both devices through two (one for each device) serially connected 1µF/2.3 kVAC capacitors. However, since neither device requires the full 3.5 kV (rms) in their operations, a Variac (variable transformer) is used to reduce the input voltage from 208 V to 175 V. One the other hand, the small transformer with a turns ratio of 1:25 steps up the 120 V line voltage directly to a proper level of 3 kV (rms). However, the 208 V line permits the torch to run at much higher power level. Thus the branch with a serially connected diode (15 kV and 750 mA rating) and resistor (1.5 kΩ) in the dotted box in Fig. 3 is removed when the 208 V power line is used. This added circuit increases the voltage applied to the torch when the diode is reverse biased. This makes it easy to initiate the discharge without increasing the turns-ratio or the input voltage of the small transformer. The series resistor added in the circuit of the torch module is used to protect the diode when it is forward biased, by preventing the charging current of the capacitor from exceeding the specification of the diode. A reduction of the capacitor charging during this period also has the effect to delay the arc discharge. This is necessary for synchronizing the arc pulse with the microwave pulse because magnetron has a higher starting voltage. The magnetron, which has a grounded anode, is then connected in parallel with a diode (15 kV and 750 mA rating) to assure that only negative voltages are applied to the cathode.

Figure 3. Schematic circuit diagram of the combined power supply.
2.4. **Performance of the power supply**

The arc discharge occurs in both the positive and negative voltage cycles of the AC input from the 208 V line and only in the negative voltage cycles of the AC input from the 120 V line; the plasma generated during negative-voltage discharges directly interacts with the magnetron output pulses, and the plasma generated during the positive-voltage discharges interacts with remaining microwave energy stored in the cavity.

The arc discharge draws too much current from the power supply for the capacitor in the magnetron circuit to maintain the required voltage for turning on the magnetron. Consequently, the magnetron is automatically turned off during the peak of arc discharge. This effect is demonstrated in Figs. 4a and b, which presents the synchronized power functions of the negative arc discharge and magnetron input as well as the power functions of the magnetron input power with and without the arc discharge. These results were obtained from low power operation of the device, where the input of the power supply was 120 V. As shown, the magnetron operation is interrupted by the arc discharge. However, arc discharge still provides seed charges to interact with the main pulse of the microwave, which extends the duration of the plasma pulse. Unfortunately, the total duration of the microwave-augmented plasma cannot be monitored by the arc current measurement. After the discharge, the voltage returns to a high value, and the output power of the “restarted” magnetron increases considerably as seen in Fig. 4b. The coupling of the two loads improves the power factor of the power line from 0.52 to 0.89.

![Figure 4.](image)

(a) Power functions of the arc discharge and magnetron input; and (b) power functions of the magnetron input without and with arc discharge.
3. Coupling Efficiency

3.1. Model of the arc torch module

The torch module has a coaxial structure and can easily be connected to a rectangular waveguide of a cross section \((a \times b)\) to form a microwave adaptor. A schematic of such an arrangement is shown in Fig. 5a. In this adaptor, the antenna size is equal to \(b\), the dimension of the short side of the waveguide, because the central electrode of the module has to pass through the waveguide to be accessible to high voltage connection for the arc discharge. This size is different from that of the conventional adaptor, which is usually less than \(b/2\). Two serially connected transmission lines shown in Fig. 5b are used to represent the torch module, i.e., the detail of the short nozzle section of the torch module, which is much shorter than the wavelength, is not included in the analysis. The central electrode is tightly fit to the ceramic insulator so that no air gap exists between the two components. The characteristic impedances \(Z_0\) and propagation constants \(\beta_0\) of these two transmission lines are determined to be (Pozar [25])

\[
\begin{align*}
Z_{01} &= \frac{60}{\sqrt{\varepsilon_r}} \ln\left(\frac{r_{01}}{r_i}\right) \Omega \\
Z_{02} &= 60 \left\{ \ln\left(\frac{r_{02}}{r_i}\right) \left[ \varepsilon_r^{-1} \ln\left(\frac{r_{01}}{r_i}\right) + \ln\left(\frac{r_{02}}{r_{01}}\right) \right] \right\}^{1/2} \Omega \\
\beta_{01} &= k_0 \sqrt{\varepsilon_r} \\
\beta_{02} &= k_0 \left\{ \ln\left(\frac{r_{02}}{r_i}\right) \left[ \varepsilon_r^{-1} \ln\left(\frac{r_{01}}{r_i}\right) + \ln\left(\frac{r_{02}}{r_{01}}\right) \right] \right\}^{1/2}
\end{align*}
\tag{1}
\]

where \(k_0 = \omega_0/c\) is the wave number in free space, \(\omega_0\) is the wave angular frequency, \(c\) is the speed of light in free space, \(r_i\) and \(r_{01}\) are the outer radii of the central electrode and the ceramic insulator, respectively, and \(r_{02}\) is the inner radius of the gas plenum chamber (central section of the torch frame).

![Figure 5](image-url)  

(a) Schematic of the microwave adaptor and (b) equivalent transmission line model of the arc torch module.
When the arc discharge is initiated, a time varying plasma is generated to be a load of the transmission line. The generated plasma acts as a resistive load to absorb the microwave power as well as an antenna to radiate the microwave power. Therefore, it is practical to consider plasma as a time varying resistive load of the combined line, represented by \( R_L \) that is the sum of the plasma resistance and the radiation impedance (resistance) of the plasma antenna. For the safety reason, a microwave leakage detector (MD-2000) was used in experiments to monitor the level of the microwave flux. It was found that the power flux at 1 m distance away was less than 1 mW/cm\(^2\), which was within the safety threshold level of 5 mW/cm\(^2\). The radiated power was estimated to be less than 5% of the magnetron input power. The antenna inside the waveguide receives the microwave power to make a current source as the input of the line. The microwave power coupling efficiency depends on the matching condition of the load. However, the plasma is a dynamic load, i.e., time varying resistive load, so perfect impedance matching over the operational range is not possible. In the following, an analysis to determine the dependence of the coupling efficiency on \( R_L \) is presented.

### 3.2. Analysis

The input impedances of line 1 and line 2 are \( Z_{i1} \) and \( Z_{i2} \) as shown in Fig. 5b. Introducing the normalized impedances \( z_{i1} = Z_{i1}/Z_{01} \), \( z_{i2} = Z_{i2}/Z_{02} \), and \( z_i = Z_i/Z_{02} \), and the notations \( a_1 = \tan \beta_0 L_1 \), \( a_2 = \tan \beta_0 L_2 \), and \( \eta = Z_{02}/Z_{01} \), allows the input impedances to be expressed as

\[
z_{i1} = (\eta z_{i2} + ja_1)/(1 + j \eta z_{i2} a_1) \quad (2)
\]

\[
z_{i2} = (z_i + ja_2)/(1 + j z_i a_2). \quad (3)
\]

Substituting Equation (3) into Equation (2), the following expression is obtained for the input impedance

\[
z_{i1} = \left[ z_i (\eta - a_1 a_2) + j(\eta a_2 + a_1)\right]/\left[ (1 - \eta a_1 a_2) + j \left( \eta a_1 + a_2 \right) \right] = R_{i1} + j \chi_{i1} \quad (4)
\]

The input impedance \( z_{i1} \) of the combined line given by Equation (4) represents the load impedance of the antenna which is expressed as a function of the actual load impedance \( z_i \) of the system. Considering only TE\(_{10}\) mode in the waveguide of Fig. 5a, the phasors of the wave fields are given by (Marcuvitz [26])

\[
E = \hat{\mathbf{y}} \begin{cases} 
\sin(\pi x/a)[A_1 \exp(-j \beta_1 z) + A_2 \exp(j \beta_1 z)] & \text{for } z < -L \\
B \sin(\pi x/a) \sin(\beta_1 z) & \text{for } -L < z < 0
\end{cases}
\]

\[
H = \hat{\mathbf{x}} \begin{cases} 
-Z^{-1}_1 \sin(\pi x/a)[A_1 \exp(-j \beta_1 z) - A_2 \exp(j \beta_1 z)] & \text{for } z < -L \\
-j Z^{-1}_1 B \sin(\pi x/a) \cos(\beta_1 z) & \text{for } -L < z < 0
\end{cases}
\]

where \( Z_1 = \omega_0 \mu_0 / \beta_1 = \eta_0 k_0 / \beta_1 \) is the wave impedance in the waveguide; \( \mu_0 \) is the free space permeability, \( \eta_0 = 377 \ \Omega \) is the intrinsic impedance of the free space, and \( \beta_1 = 2\pi / \lambda_0 \) is the wave propagation constant in the waveguide; \( A_2 = \Gamma A_1 \), here \( \Gamma = \Gamma_r + j \Gamma_i \) is the reflection coefficient.
Γ = 0 only when the load is matched to the line and the reflectance |Γ|^2 determines the coupling efficiency (given by 1 - |Γ|^2). The continuity condition of the wave electric field at z = - l leads to 

\[ A_1 \exp(j\beta_1 l) + A_2 \exp(-j\beta_1 l) = -B \sin(\beta_1 l), \]

which reduces to \( B = -(\sin(\beta_1 l)^{-1} [1 + \Gamma \exp(-2j\beta_1 l)] A_1 \exp(j\beta_1 l)) \).

This wave electric field induces an antenna current density given by

\[ \mathbf{J} = \mathbf{f} I_0 \sin(\pi y/2b) \delta(x - a/2) \delta(z + l) \quad \text{for} \quad 0 \leq y \leq b \]

(7)

where \( y = 0 \) and \( y = b \) are located on the bottom and top plates of the waveguide shown in Fig. 5a, respectively. At \( y = b \), the antenna current is \( I = I_0 \), which is the input current of the combined transmission line shown in Fig. 5b. The net time average microwave power received by the antenna is given by

\[ P_0 = -\frac{1}{2} \int \mathbf{E} \times \mathbf{H}^* \cdot dS = \frac{1}{2} \int \mathbf{E} \cdot \mathbf{J}^* \cdot dV. \]

(8)

This power should equal to the net input power of the transmission line, which is given by \( \frac{1}{2} |I_0|^2 Z_{i1} \). Thus the power balance condition leads to the following equations

\[ -\frac{1}{2} \int \mathbf{E} \times \mathbf{H}^* \cdot dS = \frac{1}{2} \int \mathbf{E} \cdot \mathbf{J}^* \cdot dV = \frac{1}{2} |I_0|^2 Z_{i1}. \]

(9)

Substituting Equations (4) – (7) into Equation (9), results in two coupled real equations for \( \Gamma_r \) and \( \Gamma_i \) being obtained. The coefficients of the equations are functions of the variable parameter \( l \) and the location of the antenna (torch module). Those coefficients are simplified by considering two preferential locations: \( l = \lambda_z/8 \) and \( \lambda_z/4 \), i.e., \( \beta_1 l = \pi/4 \) and \( \pi/2 \).

**Case A.** \( l = \lambda_z/8 \). The coupled equations are given by

\[ (1 - \Gamma_r^2 - \Gamma_i^2)/(1 + \Gamma_r^2 + \Gamma_i^2 + 2\Gamma_r + 2\Gamma_i) = -R_{i1}/\chi_{i1} \]

(10)

\[ (1 + \Gamma_r + \Gamma_i)[(1 + \Gamma_i)^2 + \Gamma_r^2]/[(1 - \Gamma_r^2 - \Gamma_i^2)^2 + (1 + \Gamma_r^2 + \Gamma_i^2 + 2\Gamma_r + 2\Gamma_i)^2]

\]

\[ = (\pi^2 aZ_{01}/16bZ_1)( R_{i1} - \chi_{i1}) \]

(11)

where \( R_{i1} \) and \( \chi_{i1} \), given by Equation (4), are functions of the load impedance \( z_i \).

**Case B.** \( l = \lambda_z/4 \). The coupled equations become

\[ (1 - \Gamma_r^2 - \Gamma_i^2)/2\Gamma_i = -R_{i1}/\chi_{i1} \]

(12)

\[ [(1 - \Gamma_r^2 + \Gamma_i^2)^2/[(1 - \Gamma_r^2 - \Gamma_i^2)^2 + 4\Gamma_i^2] = (\pi^2 aZ_{01}/8bZ_1)^2 | z_{i1} |^2. \]

(13)

These two sets of two equations [(10) and (11), and (12) and (13)] will be solved to obtain |Γ|^2(z,) for comparison.
3.3. Numerical Results

Using the dimensions of the torch device presented in this work yields $Z_{01} = 24.5 \, \Omega$, $Z_{02} = 47.4 \, \Omega$, $Z_l = 682 \, \Omega$, $\beta_{01} = 2.83 \, k_0$, $\beta_{02} = 1.83 \, k_0$, and $\beta_1 = 1.81 \, k_0$, where $k_0 = 16.33 \pi \, m^{-1}$, $a = 72 \, mm$ and $b = 5 \, mm$. Thus $a_1 = 2.1$, $a_2 = -0.72$, and $\eta = 1.93$, which reduces Equation (4) to $z_{i1} = [1.03 \, z_i + j(0.18 - 0.75 \, z_i^2)]/(1 + 0.72 \, z_i^2) = R_{i1} + j\chi_{i1}$. With the aide of these parametric values, Equation sets (10) & (11) and (12) & (13) are solved numerically. The results $|\Gamma_A|^2(z_i)$ and $|\Gamma_B|^2(z_i)$ are presented in Figs. 6a and b, respectively. As shown in the figures, $|\Gamma_A|^2 < |\Gamma_B|^2$; moreover, $|\Gamma_A|^2 < 0.2$ for $38 \, \Omega < Z_L < 200 \, \Omega$, while $|\Gamma_B|^2 > 0.2$ in the same region. This impedance region corresponds to the times before and after the peak of the arc discharge. In the setup, the magnetron and the arc torch module share the same power supply to eliminate the need of an additional circuit to synchronize the microwave pulse with the arc discharge. Hence, the magnetron operation is affected by the arc discharge, which causes voltage to drop considerably. As shown in the preceding section, the magnetron is off during the peak of the arc discharge due to the voltage drop during the arc discharge. In other words, during the high reflectance time period when the plasma torch has very low impedance, the voltage drop automatically shuts off the magnetron. This automatic shutoff feature also improves the coupling efficiency of this microwave adaptor. The results presented in the next section are obtained by using Case A arrangement with $l = \lambda_z/8$.

4. Microwave Effect on the Plasma Torch

The torch is operated in the open air using compressed air as the feedstock. The torch module operates stably over a very large flow rate range, with flow speeds from subsonic to supersonic. The added microwave power has a significant effect on the size and enthalpy of the plasma torch, which varies with the gas flow rate and the power supply.

This effect is demonstrated by the single frame (exposure time of 1/60 sec.) CCD plasma plume images shown in Figs. 7 and 8, which correspond to torch run by power supplies of 175/120 V input, respectively. The five sets of images in each figure with microwave off (top
row) and on (bottom row) correspond to the air supply pressures of 1.36, 2.04, 3.4, 4.76, and 5.44 atm absolute, respectively, where the flow speeds at the nozzle exit of the torch module are subsonic in (a) to (c) and are supersonic in (d) and (e). It is noted that there are two arc plasma plumes in each image of Fig. 7 while only one in each of Fig. 8. This is a reason, in addition to that of different power supplies, why the images in the top row of Fig. 7 are more intense than the corresponding ones in Fig. 8. As shown in both figures, the applied microwave power increases the height and the volume of the plasma torch significantly at low gas flow rates. Comparing the top- and bottom-row plume images in Figs. 7(a) to (e), it is seen that, with the application of microwave power, the respective plume heights increase by more than 300%, 100%, 30%, 20%, and 10%, and the respective plume volumes increase by approximately 900%, 400%, 180%, 100%, and 50%. The enhancement is estimated from the increased luminosity of the plasma plume, which provides an indirect measurement. The effect of applying the microwave power decreases with increasing flow speed. A similar trend is also observed in Fig. 8. As the air supply pressure is increased, thereby increasing the flow speed, the size of the arc plasma torch shown in the top rows of Figs. 7 and 8 also increases except at the transition from subsonic (c) to supersonic (d). The plume intensities in the top row of Fig. 7 are much higher than the corresponding ones in the top row of Fig. 8, due to much larger discharge powers being applied. Alternatively, the plume sizes of the microwave-enhanced plasma torches shown in the bottom rows of Figs. 7 and 8 decrease with increasing flow speed but are still enhanced compared the arc only images as indicated by lower luminosity of the arc only plasma plumes.

This dependence most likely results from the fact that the fixed applied power has to energize more gas with less interaction time as the flow rate increases, and the size of the plasma torch becomes dictated by the flow speed. At the same supply pressure, the heights of the microwave-augmented plasma torches shown in (d) and (e) are only slightly larger than the corresponding arc plasma torches. However, the volume and the luminosity intensity of the plasma plume are still increased by the application of the microwave power.

**Figure 7.** Images of plasma plumes produced, by the power supply using 175 V input, before (top row) and after (bottom row) the magnetron is turned on. The air supply pressures in (a) to (e) are 1.36, 2.04, 3.4, 4.76, and 5.44 atm.
Figure 8. Images of plasma plumes produced, by the power supply using 120 V input, before (top row) and after (bottom row) the magnetron is turned on. The air supply pressures in (a) to (e) are 1.36, 2.04, 3.4, 4.76, and 5.44 atm.

Clearly, the microwave can significantly increase the volume and the brightness of the torch, in particular, at low airflow rates, where the brightness is a reasonable indicator of the plasma enthalpy. A torch in this arrangement is particularly attractive to the application for igniting the hydrocarbon-fuelled scramjet engine. This is because 1. the torch module of this torch system can still be easily plugged to the engine along with a required seal to high-pressure gas; 2. the microwave feature in this new torch system adds additional microwave power to the plasma; and 3. the microwave field is not affected by the supersonic crossflow in the combustor, thus the microwave plasma torch generated at relatively low airflow rate can still penetrate deeply into the supersonic cross flow. Operating at a low flow rate further enhances the enthalpy of the plasma torch, which helps to reduce the ignition delay time and to increase the rate of combustion of hydrocarbon fuels. These advantages are essential to the operation of the engine.

5. Microwave Effect on the Electric Characteristics of the Torch

The time varying voltage $V$ and current $I$ of the discharge were measured using a digital oscilloscope (Tektronix TDS3012 DPO 100 MHz and 1.25 GS/s). The product of the $V$ and $I$ functions gives the instantaneous power function. The results depend strongly on the power supply.
The power of the 60 Hz arc discharge. (a), the positive arc (PA) and negative arc (NA); (b), microwave field applied to the positive arc (PA+M), and negative arc (NA+M).

Figure 9. The power of the 60 Hz arc discharge. (a), the positive arc (PA) and negative arc (NA); (b), microwave field applied to the positive arc (PA+M), and negative arc (NA+M).

5.1. Power supply of 175 V input

The arc discharge occurs in each half cycle, but magnetron runs only during the negative-voltage half cycle. Thus, the microwave pulse lasting approximately 6 ms is expected to synchronize only with the negative discharge pulse. However, the operation of the magnetron is affected by the arc discharge. In fact, as shown in Fig.3a the magnetron is shut off during the mainpulse of the arc discharge. It turns out that the microwave effect on the positive discharge is stronger than that on the negative discharge in the case of low flow rate. The power functions in one cycle for discharges without and with the presence of microwave in the case of low flow rate are presented in Figs. 9a and b for comparison. The supply pressure of the torch module is 1.16 atm. The powers plotted in Fig. 9 are calculated from the current drawn by the arc discharge and the voltage drop across the two electrodes, i.e., no contribution from the magnetron is included. As shown, the microwave has enhanced both the peak power of the negative discharge and the positive discharge. The peak power in the negative discharge pulse is increased from 8 kW to 12 kW. On the other hand, the total energy per pulse decreases slightly due to the decrease of the pulse length. It is noted that the discharge pulse energy is limited by the available energy stored in the capacitors. In the arc discharge, the voltage and current peaks are not in phase. The voltage reaches the peak of about 4 kV when the gaseous breakdown starts. As the discharge current
increases, the discharge voltage drops rapidly to a relatively low level in the range of 200 to 400 V. Thus, at the peak current the discharge voltage is in fact quite low, which limits the peak discharge power. The microwave helps to reduce the phase delay of the current peak from the voltage peak resulting in a higher discharge voltage while the discharge current is increasing. The V-I characteristic plots shown in Figs. 10a and b, for discharges without and with the presence of microwave, respectively, also demonstrate this point. As shown the peaks of the arc discharge currents in both cases are about the same. However, the areas of the hysteresis loops in Fig. 10b are larger than the corresponding ones in Fig. 10a, and the arc discharge voltages at large current values (Fig. 10b) are higher. Consequently, the peak of the product of the V and I functions is increased. It is also indicated in Fig. 10b that microwave increases considerably the breakdown voltage in the positive discharge. It is understood that the discharge initiates in the region near the central electrode where the applied electric field concentrates due to the cylindrical geometry. When the central electrode is positive, it collects electrons produced nearby by the discharge. The microwave field introduces radially quiver motions in electrons. Since the microwave frequency is much smaller than the electron collision frequency, the mean free path of electrons is essentially determined and thus enhanced by the quiver speed; this then increases the transit-time loss of electrons to the central electrode, which in turn increases the breakdown voltage. The microwave effect on the positive discharge is likely attributed to the circuit arrangement and cavity setup. The negative arc discharge delays the start of the magnetron as shown in Fig. 4a and the cavity prolongs the storing time of the remaining microwave after the negative arc discharge.

5.2. Power supply of 120 V input

The microwave effect on the arc discharge can be seen by comparing the images shown in Fig. 11. Fig. 11a is an image of the arc plasma plume recorded by a CCD camera with a 20 µs exposure. The high intensity region was correlated to the arc loop of the discharge. As microwave was introduced, the emission along the arc loop was intensified as seen in Fig. 11b. Clearly, the microwave energy has significantly enhanced the volume of the arc loop and the enthalpy (evidenced by the luminosity) of the arc plasma. Most significantly, the plasma has a wider distribution in the central region of the hollow central electrode where the fuel is ejected.
The cycle energies of the arc discharges (with microwave off and on) and the magnetron input as functions of the supply pressure are presented in Fig. 12. As shown, without microwave the cycle energy of the arc torch is about 4 J, which is less more than a half of the cycle energy of the arc torch run by the power supply of 175 V input and is too low to be an igniter. Adding microwave, the cycle energy of the arc discharge, in fact, decreases. This is due to the power handling capability of the power supply, which cannot handle the power demands from the arc torch and the magnetron simultaneously. This was not the case when the power supply of 175 V input was used. Nevertheless, the torch’s total energy (Arc with MW on + 80% of Magnetron input) is enhanced significantly to about 12 J/cycle (assuming that magnetron has 80% conversion efficiency), which is sufficient for the ignition application.

6. Emission Spectroscopy and Electron Temperature

Emission spectroscopy of the torch run by the power supply of 120 V input is studied. It is found that there are two dominant groups of lines in the spectra. The first group includes the Fe I \([4p(y3F^*)-4\xi(a3F)]\) lines, representing the emission of contaminants; the second group is the atomic oxygen (O I) lines in the spectral region between 777.1 and 777.6 nm. It turns out that the relative intensities of the \(4p(z5D^*)-4s'(a5D)\) series of Fe I transitions can be used to determine the electron excitation temperature. Additionally, the atomic oxygen in the plasma effluent is an indication of energetic electron flux produced in the torch. This is because the required energy to dissociate an oxygen molecule into two oxygen atoms is quite high; the reaction: \(e + O_2 \rightarrow 2O + e\), has a reaction rate coefficient [27] \(k_1 = 4.2E-9exp(-5.6/T_e)\), where \(T_e\) is in eV. This reaction rate decreases rapidly with \(T_e < 5.6\) eV; thus it needs about 5 eV electrons to effectively dissociate \(O_2\) into atomic oxygen.
Figure 12. The dependency of the cycle energies of the arc discharges and the magnetron input on the supply pressure.

Figure 13. Schematic diagram of the experimental setup for measurements of the emission spectroscopy of the torch.
The schematic diagram of the experimental set-up [24] is shown in Fig. 13. A 5 µm x 2.5 mm section of the torch plume was imaged with a quartz telecentric lens system to the entrance slit of a 0.5 m imaging spectrometer (Acton) with a coated 1800 g/mm grating, blazed at 500 nm. Possible effects of the second order spectrum were eliminated with a glass filter in front of the entrance slit. In order to provide a wider spectral frame, in some observations a 600g/mm grating, blazed at 1 µm, was used. The detection system consisted of an Acton imaging spectrometer with an Apogee camera and a Hamamatsu CCD detector (1024x256 pixels). Pixel size of the detector was about 25 µm.

6.1. Iron and Atomic Oxygen Lines

In the torch, there are many metallic contaminants, predominantly Fe, but also Cr, Ni, and Mn, present in the form of particulates in the solid phase. In measurements, the emission spectrum was taken from a location about 2 cm above the torch nozzle. Fe I and O I lines were dominant in the spectra. Molecular emission spectrum of Nitrogen and Oxygen is practically nonexistent.

![Figure 14. Relative integrated intensity of oxygen lines in the spectral region between 777.1 and 777.6 nm, from a fixed location in the torch.](image)
Figure 15. Relative integrated intensity of the Fe I [4p(y 3F*)-4s (a3F)] line, representing the emission of contaminants.

Figure 16. Ratio of emission intensities of Iron and Atomic Oxygen lines.
The dependence of atomic oxygen content in the torch on the supply pressure (i.e., flow rate) is illustrated in Fig. 14. It is shown that in the absence of microwave the oxygen content increases as the flow rate increases. This is realized by the fact that the required breakdown field for the discharge increases with the flow rate, thus more energetic electrons are produced as the flow rate increases. When microwave power is applied the oxygen content is further increased. The microwave effect is diminished only in very high flow rate regime (i.e., supply pressure > 4 atm; the flow speed at supply pressure of 4 atm was determined experimentally to be near sonic). At 2.04 atm, the emission intensity is more than an order of magnitude higher. The intensity drops to non-microwave levels at high flow rates, probably due to the decrease of the available interaction time between electrons and microwave. It is noted that intensive microwave appears only in the region near the nozzle of the torch module. A similar dependence on the flow rate for the integrated intensity of the Fe I emission lines, with and without adding microwave to the discharge, is shown in Fig. 15. It shows that volatile metallic contaminants are also strongly excited in the torch in the presence of microwave power. However, the ratio of the emission intensities of Iron and Atomic Oxygen lines is not strongly affected by the presence of microwave. As shown in Fig. 16, this ratio is steadily reduced with the flow rate; trend is similar and the magnitude is about the same with and without microwave power. This correlation is consistent with the understanding that the iron particulates come from ablating the outer electrode (anode) of the module by the energetic electrons and dissociation of oxygen molecules into atoms also requires energetic electrons. The ablating process appears on the (electrode) surface and the dissociation process occurs in the (gas) volume. Thus the effectiveness of energetic electrons in two processes decreases with the flow rate at two different rates; it explains why the ratio decreases as the flow rate increases.

6.2. Electron Excitation Temperature

Emission lines from partially evaporated particulates are very abundant and their intensities reflect the plasma conditions in the torch. However, the diagnostics of the torch is complicated by the presence of many metallic contaminants. In order to determine electron temperature in the plasma, we used the 4p(z5D*)-4s2(a5D) series of Fe I transitions. The choice was dictated by the heavy presence and interference of other metallic species. Since the discharge is in periodic mode, only the peak value of the electron excitation temperature will be determined.

Microwave power excites more or less uniformly all species found in the torch and the degree of excitation depends on the electron excitation temperature [28], which is usually higher than the electron temperature because low energy electrons in the distribution do not contribute to the excitation. Flow-rate dependence of the electron temperature in the torch with and without microwave power is presented in Fig. 17. It shows a strong increase both with the microwave power and supply pressure. The trend is real, although the accuracy of temperature values is poor, due to the effect of contaminant lines. It is noted that the location of measurements was fixed to about 2 cm above the torch nozzle; on the other hand, the size of the torch depended strongly on the flow rate, in particular, in the presence of microwave.

Therefore, the electron excitation temperature presented in Fig. 17 may not be the temperature of the hottest spot in the torch. Without microwave, the electron temperature, starting at 2.04 atm, decreases as the supply pressure increases, except, at 3.4 atm, where the
temperature increases considerably. This anomaly might indicate that the measurement caught a localized hot spot in the torch. With microwave, the temperature increases rapidly with the increase of the supply pressure. This is correlated to the decrease of the size and volume of the torch with the increase of the supply pressure as shown in Fig. 8. In other words, the microwave hot spot of the torch at low flow rates is above the observation point. It shifts down as the flow rate increases. The sudden drop at 4.76 atm indicates that the microwave hot spot becomes below the observation point; suggesting that, under such a high flow (supersonic) condition, microwave is no longer coupled out of the torch module effectively. The electron excitation temperatures presented in Fig. 17 are rather high; however, it is noted that the discharge is in periodic mode, thus the electron plasma is not in thermal equilibrium with ions and neutrals.

7. The ignition capability of the plasma torch

Experiments demonstrating the torch module as an igniter and pre-ignited fuel injector of hydrocarbon fuel were performed. The torch was run with the power supply operated at 208 V input. Tests have been conducted using gaseous ethylene fuel with the flow rate of 9 standard liters per minute (SLM) injected through the central electrode, a tungsten-carbide tube, corresponding to 160 m/s fuel velocity at 298 K. The flame plume was observed when the torch was run with airflow rates ranging from 10-100 SLM with microwave power applied. This airflow rate range corresponded to air velocities of 6-65 m/s at 298 K. Ignition under these conditions is illustrated in Fig. 18b. The plasma plume of the arc discharge (without microwave)
operated in the same condition is shown in Fig. 18a for comparison. As shown, the fuel was not ignited in Figure 18a. This effect is understood because fuel was injected from the central port of the module, which is outside the main arc discharge region. An estimate of the discharge region can be seen in the images shown in Fig. 19. Fig. 19a is the arc plasma plume emission image recorded with an interline-transfer CCD camera with a 100 µs exposure. This image was recorded through a 1 nm bandpass interference filter centered at 405 nm, and the high intensity region was correlated to energy deposition by the plasma. The use of a narrow bandpass filter was necessary in order to prevent saturation of the CCD camera allowing the discharge region to be clearly imaged. As microwave is introduced, the plasma torch distributes more uniformly across the electrodes as seen in Fig. 19b, i.e., the discharge becomes more cylindrical. In Fig. 19b, the plasma distribution is more uniform and has a higher density in the central region of the hollow central electrode where the fuel is ejected. The microwave energy has also significantly enhanced the size and enthalpy (evidenced by the luminosity contrast shown in Figs. 7 and 8) of the plasma torch. It is noted that the arc discharge alone can also ignite the fuel as increasing the discharge energy by increasing the capacitance in the power circuit for the arc discharge from 1 µF to 3 µF and the airflow rate. Maintaining the ethylene flow rate at 9 SLM, fuel was ignited with a maximum of 400 SLM airflow rate. The results presented in Figs. 18b and 19b demonstrate that the microwave-augmented arc discharge operating with low airflow rate can deliver enough energy to the gas over a larger volume to ignite the fuel. Low airflow rate operation is an essential requirement of a practical igniter.

**Figure 18.** Torch plasmas plumes, (a) air plasma generated by arc discharges and (b) flame plume (in the center) ignited by 60-Hz microwave plasma torch; in both cases gaseous ethylene fuel (flow rate of 20 SLM) was injected through the central electrode (tungsten-carbide tube), and an airflow rate of 30 SLM was supplied.
Figure 19. Plasma plume emission images recorded, though a 1 nm bandpass interference filter centered at 405 nm, with an interline-transfer CCD camera set with an 100 µs exposure; the illuminated portions shown correspond to the discharge region generated by (a) an arc discharge and (b) an arc discharge in the presence of the microwave.

8. Summary and Conclusions

We have designed, assembled and characterized a versatile modular plasma torch for the application as an ignition aide for a hydrocarbon-fueled scramjet engine. The most unique features of this new torch module are 1) using an arc torch module as a microwave adaptor of a tapered rectangular waveguide cavity, and 2) having a hollow central electrode to add a fuel injection port. In this setup, microwave couples through the torch module, as a transmission line, to the plasma torch, which is generated by the arc discharge between the electrodes of the module. A theoretical analysis on the microwave coupling efficiency shows that nearly 80% of the supplied microwave power can be delivered to the arc plasma through this adaptor arrangement. The experimental results indicate that the coupling could be better, judged by the relatively low temperature elevation of the cavity.

The effects of added microwave on the size, volume, peak power, cycle energy, emission spectral intensities, and electron excitation temperature of the plasma torch are explored. Experiments performed demonstrate that the added microwave energy increases the height and the volume of the plasma torch considerably. The magnitude of the microwave enhancement decreases as the airflow rate increases. Nevertheless, the height and the volume of microwave-augmented plasma torch exceed those of the arc plasma torch even when the flow speed is supersonic. The added microwave power enhances the peak power delivered by the arc discharge by reducing the phase difference between the current and voltage. The addition of the magnetron to the circuit also increases the circuit efficiency enabling more power to be delivered to the gas.

These observations verify the profound microwave effects on enhancing the capability of the torch for igniter/fuel injector applications. For instance, the added
microwave triples the energy of the torch, run with a small compact power supply, to about 12 J/cycle (peak power exceeds 6 kW). It enhances the electron excitation temperature by a factor as large as 6, measured via emission spectroscopy. These enhancements enable the torch to ignite hydrocarbon-fuels.

The principal advantages of this arc-microwave hybrid torch module discussed here are: 1) It is compact (including the power supply), portable, light weight, and durable, running for long periods of time in a periodic mode on an air feedstock; 2) It needs very low gas flow rate in its operation, which is an essential requirement of a practical igniter; 3) It is able to run as a combined igniter/fuel injector. The microwave-augmented arc discharge operating with low gas flow rate delivers more energy to the gas over a larger volume, as evidenced by the measured cycle energy and luminosity of the plasma plume and the electron excitation temperature, compared with arc discharge alone. The improvements on the thermal energy as well as the penetration depth (into the combustor) of the plasma torch should both prove beneficial for applications involving ignition and combustion in a variety of environments.

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References


