

Stabilization of a Sub-limit lean premixed flame by Centralized-microwave burner

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1 Introduction

Recently, atmospheric-pressure microwave plasma sources have found many specific applications in different industry sectors. On the one hand, they can be used for treating surfaces such as cleaning and etching. On the other hand, specific outstanding applications are recently explored in the field of combustion. Plasma-assisted combustion is particularly well suited for using in challenging conditions where complete and stable combustion is exceedingly difficult using traditional methods. Several studies have shown recently, that the application of a nanosecond pulsed plasma to hydrocarbon combustion significantly increases the stability of premixed flames [1–7]. In these studies, plasma has been used either to reduce the ignition delay time (IDT) or to extend the lean flammability limit (LFL) [8] as evidence of flame stability enhancement resulting from the application of the plasma discharge. The reaction zone of a flame is one of rapid, non-equilibrated chain reactions and the flame structure is governed by chemical kinetics and flow interactions. In hydrocarbon flames complex reactions also create ions and electrons in its high-temperature stream, therefore, the flame itself is regarded as a kind of plasma. By affecting the ion motions and electron temperature in the flame, microwave is shown to effectively enhance and stabilize the flame in the sub-limit lean premixed region. Sullivan's [5] research result has yielded an increase of laminar flame speed by up to 65% in the rectangular cavity by addition of microwave power of about 2500W. In the experiments conducted, microwave energy is only absorbed into the thin flame region and does not lead to breakdown elsewhere. In order to concentrate the microwave energy and enhance the absorption of microwave energy by the flame, in this work, a novel design of centralized-microwave burner is used to incorporate microwave (2.45 GHz) electromagnetic energy directly into the reaction zone of a premixed laminar methane–air flame for flame enhancement and stabilization. The current results show that a plasma source under atmospheric pressure is successfully generated with addition of microwave power about 300W. With the onset of a plasma flame by microwave, greatly broadening of the stable lean flammability limit to an equivalence ratio of 0.38, far below the lean flammability limit of the methane flame can be achieved.

2 Experimental Setup

A novel concentrated-microwave-jet burner system is developed in collaboration with electrode antenna technologies to directly couple microwave energy into flames. A schematic of the experimental setup is shown in Fig. 1, which contains microwave generator, directional coupler, rectangular waveguide, resonant cavity and concentrated-microwave jet burner. The microwave energy is generated by a research-grade 2.45-GHz magnetron directly mounted to a WR430 waveguide and powered by an SM840 power supply. Microwave radiation can be generated in excess of 1.8 kW. The microwave is introduced into a rectangular TE (transverse electric) mode waveguide. The microwave transmission inside the WR430 waveguide is in TE₁₀ mode, for the TE₁₀ mode, the electric field strength is greatest and nearly constant in the waveguide and connects to the resonant cavity in the ends. A directional coupler is mounted next to the magnetron head and is used to measure the incident power. A circulator is used to direct reflected energy into a dummy load with a coupler, so that reflected energy can also be measured. The jet burner is made of quartz tube with inside diameter of 5mm. In order to concentrate the microwave radiation, an electrode antenna made by tungsten is inserted into the center of the burner. The electrode geometry is specially optimized for plasma ignition by delivering a high electric field at the electrode tip. Methane and air streams are controlled and measured with calibrated mass flow meters and mixed in the supply line and burner. Mixture temperature was about 298K. A spectrometer (Ocean Optics, USB4000) is used for analyzing the emission spectra ranging from 350 to 900 nm.

3 Results and Discussions

Numerical simulation of the concentrated-microwave burner

To aid in the design of the electrode, the electric field was calculated numerically from Maxwell's equations using the "RF Electromagnetic Solver" module of the program COMSOL MultiPhysics 3.4. Figure 2 is the numerical solution with 2.45 GHz microwave excitation. This simulation provides a relative 3-D electric field distribution within the cavity structure. For our simulation, the medium inside the cavity is air, and all boundaries are set to be perfect electrical conductors. Figure 2 shows that there is a strong electric field on the top of the electrode antenna, which means this device is suitable for concentrating microwave energy.

Microwave-flame-coupled plasma

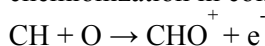
Figure 3 is the flame shape (a) without and (b) with microwave energy of 300W under the same condition of equivalence ratio $\Phi=1.2$. Figure 3(b) shows that plasma discharge is initiated when the distance between the flame and electrode is less than 1mm. This results from when the E-field reaches the breakdown threshold, air around the electrode tip will be ionized, generating a plasma discharge that sits entirely above the tip of the electrode. The focus of the electromagnetic energy into the tip of the electrode is enhanced as the radicals and the weak concentration of electrons in the flame amplify the coupling process. Clearly, the coupling of microwave power into the premixed flame changes the physical appearance of the flame, and the microwave energy coupling is more efficient by the design of electrode antenna.

Emission spectrum of plasma-hybrid flame

Optical emission wide scans of combustion only and combustion with the addition of 400 W of microwave power into the combustion flame are depicted in Fig. 4. The emission spectra are scanned from 350 to 900 nm visible wavelength. Clearly, with 400 W addition of microwave power to the premixed flame, the intensity of the spectra increases dramatically compared to combustion only. This clearly indicates that the microwave energy input alters the flame structure and combustion characteristics. The nitrogen electronic excitation and enhancement of radicals, such as CH and OH are also detected when microwave power is added into the flame.

Flammability limits

In terms of flammability limits, i.e., the limit of the flame to sustain itself in a fuel lean mixture ratio, the extension of the plasma-assisted flame to leaner burning operating conditions with and without microwave enhancement is shown in Fig. 5. We conduct the blowout tests by maintaining the methane flow rate constant and varying the air flow rate until the flame blows out. The x-axis of the graph represents the fuel flow rate and the y-axis represents the equivalence ratio. Clearly, significant improvement in the flammability limit with the microwave coupled plasma flame can be found. The results show that with the onset of a plasma-assisted flame induced by microwave can broaden the stable lean flammability limit to an equivalence ratio of 0.38, far below the lean flammability limit of the methane flame. It is well known that the primary ionization mechanism is the associative chemionization in collisions of CH radicals and oxygen atoms:



At higher total flow rates, more heat release from combustion with relatively less heat loss to burner leads to higher temperatures, which results in more CH and subsequently more electrons. This results in more OH production for higher flow rates. Since microwave absorption in the neutral molecular gas is negligible, microwave is found to couple to the charged particles generated in the flame and enhances the flame chemical reaction and flame burning velocity. It is believed that the microwave fields principally heat the electrons of the flame, and the hot electrons transfer energy to the reacting species. The resulting increase in the population of higher vibrational states of the reacting species, especially that of oxygen, is said to increase reaction rates in the flames and extend the plasma-assisted flame to leaner burning operating condition.

4 Conclusions

By affecting the ion motions and electron temperature in the flame, microwave is shown to effectively enhance and stabilize the flame in the sub-limit lean premixed region. In this research, a novel centralized microwave jet burner system is proposed for fundamental studies of the stabilization mechanism of the sub-lean limit flames. The control parameters and operation characteristics of the integrated microwave burner system is further investigated. The microwave energy is enhanced and applied to the combustion system by means of a rectangular resonant cavity. In order to concentrate the microwave energy and enhance the absorption of microwave energy by the flame, a novel design of centralized microwave burner is used to incorporate microwave (2.45 GHz) electromagnetic energy directly into the reaction zone of a premixed laminar methane–air flame for flame enhancement. The results show that with the onset of a plasma flame by microwave, a significant rise in excited state species, CH and OH radical numbers can be observed and the addition of microwave is shown to broaden the stable lean flammability limit to an equivalence ratio of 0.38, far below the lean flammability limit of the methane flame.

5 Figures

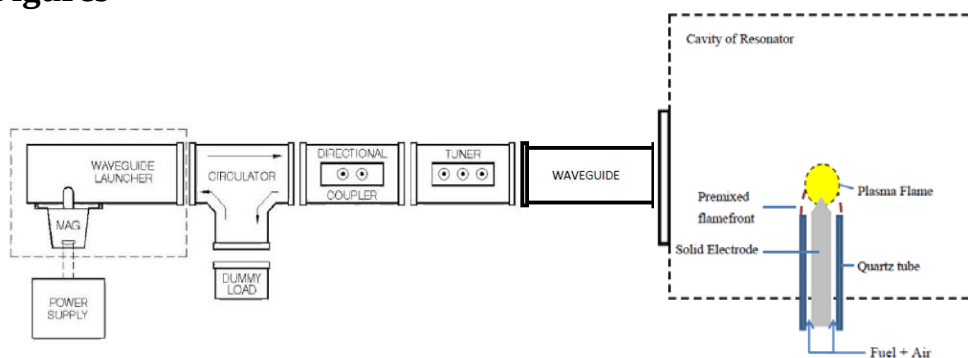


Figure 1. Schematic of the centralized-microwave burner system

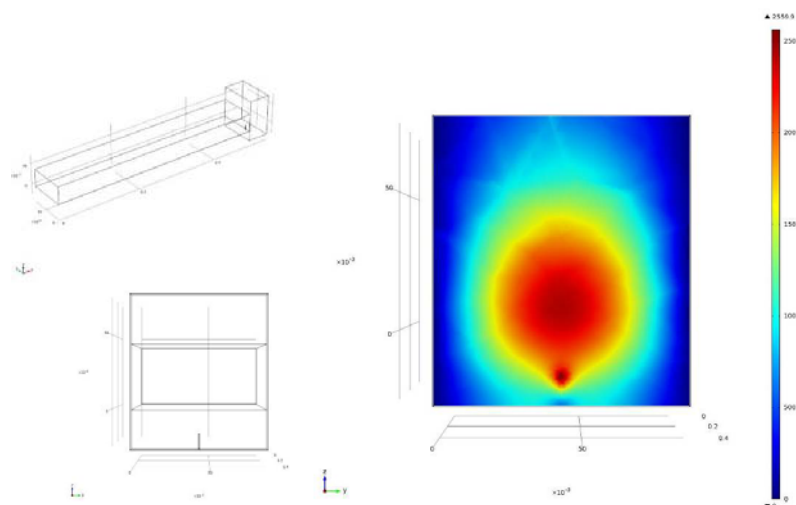


Figure 2. Numerically calculated relative electric field distributions inside the cavity with no flame/plasma

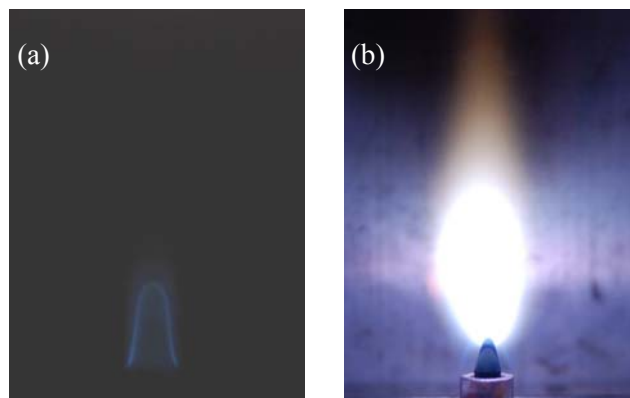


Figure 3. Photograph of Methane/Air premixed flame (a) without and (b) with microwave radiation at $\Phi=1.2$

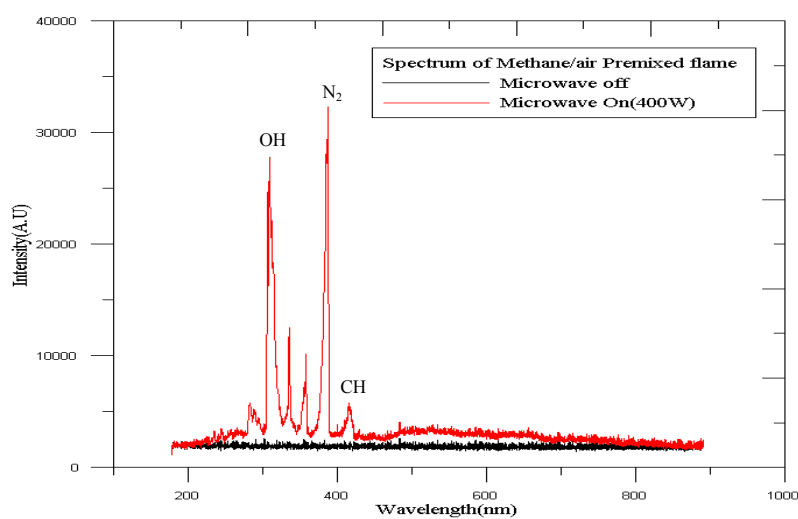


Figure 4. Optical emission wide scans of combustion only and combustion with the addition of 400 W of microwave power into the flame

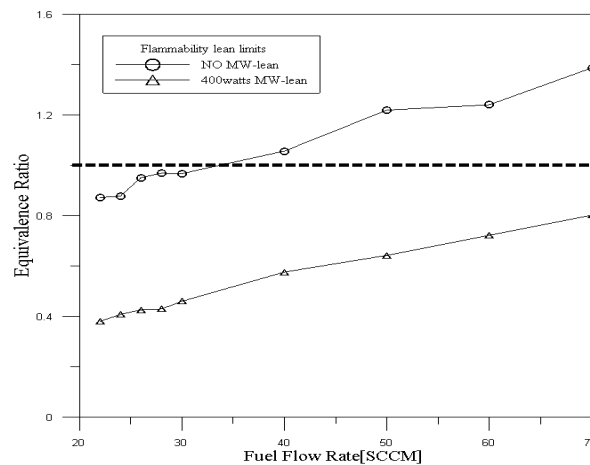


Figure 5. Flammability limits for methane/air flame (lean) with no microwave radiation and 400 W microwave radiation (dash line: $\Phi=1.0$)

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