A study of flame enhancement by microwave induced plasma: the role of dilution inert

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1 INTRODUCTION

Recently, there has been growing research interest in plasma-assisted combustion (PAC) in combustion processes, as the plasma-assisted approach provides a useful method to stabilize the flame, especially in lean conditions. Results of experimental and computational research into plasma ignition and combustion have been reported [1–5]. Different enhancement mechanisms have been proposed and investigated, including the chemistry of ions, excited species, etc. While numerous results have shown the attractive plasma enhancement effects in each of the PAC processes, challenge for complete understanding of PAC mechanisms still remains. In PAC, plasma provides energetic electrons and sources of reactive species to induce dissociation, ionization, and vibrational and electronic excitation of the other neutral molecules. Key radicals and neutral species in the common hydrocarbon flame include H, O, O_2, OH, CH, CO, NO, NH, HCO, NO_2, CH_2, C_2H_2, etc. more than 50 key species and more 200 reactions are typically included in order to have a comprehensive description of the reaction kinetics. Current understanding of the roles of reactive species (radicals, ions, and excited neutral species) in PACs is still in debate, and the kinetic mechanisms and pathways of the reactions involving radicals as well as other reactive species still remain to be explored [6]. Therefore, it would be helpful to investigate reaction pathways by first tracing a specific reactive species, e.g. OH radical in PAC process with different combustible mixture. Low temperature, nonthermal microwave plasmas that have high power coupling efficiency, excellent flexibility, rich free radicals and other reactive species [7–12], are very suitable for PAC systems. In Hemawan et al.'s work [13], they used a highly efficient direct-coupling method in a specially-designed chamber, where plasma is generated spatially coincident with the flame reaction zone, enabling plasma-induced flame enhancement at low power levels. However, it would be difficult to separate a flame speed enhancement from plasma or microwave for fundamental flame studies. In order to clearly distinguish the interaction between the flame and microwave induced plasma for further studies of the microwave/plasma flame enhancement and stabilization process and mechanism of the flame, a novel low-power microwave/plasma burner system is proposed in this paper that further concentrates the microwave energy and enhances the absorption of microwave energy by the flame with easy optical accessibility for experiments. In the proposed burner setup a low-power plasma is initiated by a sharp-tip electrode antenna and integrated in the close vicinity of the flame in the microwave resonant cavity for flame enhancement and stabilization. The research objective of this work is to use this novel setup to explore the role of the

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dilution inert in the flame enhancement by using microwave induced plasma. Digital imaging and optical emission spectroscopy (OES) are employed as diagnostic tools to perform parametric characterization of the microwave/plasma-assisted flame by the replacing nitrogen in the air by argon.

2 Experimental Setup

The concept of the proposed microwave/plasma burner is to use the electrode antenna to concentrate the microwave power and use the ions and electrons in the flame to help ignite and maintain a low-power plasma in the vicinity of the flame to directly impose energy onto the reaction nzone of the flame for flame stabilization. A unique concentrated-microwave/plasma jet burner is developed based on this concept for further studies of the flame enehancement of the PAC system. The jet burner is made of a quartz tube with an inner diameter of 10 mm. In order to concentrate the microwave radiation, a sharp-tip electrode antenna made of tungsten is inserted in the center of the burner. Tungsten electrode can form a clean, ball-shaped plasma tip when heated, providing great arc stability and sufficient material strength under high temperature plasma environment. The electrode geometry is specially optimized for plasma ignition by delivering a high electric field at the electrode tip. The details regarding this proposed burner are shown in Figure 1. In the figure, it shows (a) a photograph of parts of the system along with an insert picture of a methane/air premixed flame; (b) the corresponding schematic of the burner setup. In this experiment, the microwave excitation frequency is 2.45 GHz, and the cavity is excited in the TEM rectangular wave mode. The whole microwave/plasma burner system includes the following major components: (1) a quartz tube burner; (2) an adjustable endplate; and (3) a mono-pole electrode as the antenna. When the relative location of the jet burner, antenna, and endplate are adjusted using the micrometer-actuated uni-slide translator with an accuracy of 0.05 mm, an optimized resonant mode can be achieved wherein most of the energy is focused on the tip of electrode. The high strength electric field and the presence of microwave-induced plasma in the interaction both require measurement assessment using non-intrusive optical techniques. The cavity resonator is furnished with a mesh window to allow optical access without detrimental interference of the resonator and spectroscopic optical diagnostics on spectra intensity is also performed in this study. A spectrometer (Ocean Optics, USB4000) is used for analyzing the emission spectra ranging from 350 to 900 nm. The emission was focused using a spherical lens (f = 50 mm) through a pin-hole filter to isolate the reaction zone.

3 Results and Discussions

Microwave induced plasma flame

Figure 2 shows the flame shapes for (a) CH_4+(20%O_2/79%N_2) mixture and (b) CH_4+(20%O_2/79%Ar) mixture with microwave energy of 100W under the same condition of equivalence ratio Φ=1.5. Figure 2 clearly shows that plasma discharge is initiated when the E-field reaches the breakdown threshold. The principal mechanism through which the plasma discharge affects the flame parameters is the change in the mixture composition of energetic excited species and radicals, such as electron, N_2*, Ar* and O atom in the stream, which initiate additional chain reactions in the pre-flame zone. Applying non-equilibrium plasma, one can find that electronic excitation of the mixture components induces enhanced production of active particles (in particular, atomic oxygen) resulting in flame enhancement. According to the optical spectroscopic results in Figure 2, the production of these active radicals such as OH can be found in the plasma discharge and directly goes into the reaction zone of flame which causes the acceleration of the processes governing the combustion rate and the flame propagation velocity. Clearly, the flame enhancement by plasma is more intense in Figure 2 (b), which means the microwave energy coupling is more efficient when N_2 in the oxidizer stream (air) is replaced by Ar.

Emission spectrum of plasma discharge

Optical emission wide scan of plasma discharge is shown in Figure 3. The emission spectra are scanned from 350 to 900 nm visible wavelength and these emission spectroscopy measurements serve

only as qualitative plasma diagnostics. Emission spectroscopy measurements suggest that OH radical generated in the plasma may be the key species for plasma chemical fuel oxidation and subsequent ignition. This active radical is the most important chain radical for combustion reactions. In Figure 3 (a), it can be seen that traditional N_2 (violet band system) radicals are detected in the plasma. The OH ($A^2\Sigma^+$) 308 nm radical is also detected in this area. The OH band systems, usually detected in hydrocarbon-air flames, are the most pronounced feature of the present plasma assisted flame spectra. The spectrum of N_2 band comes from the electronically excited states of N_2, $N_2 + e^- \rightarrow N_2^* + e^-$. The O atoms are primarily formed both by electron impact, $O_2 + e^- \rightarrow O + O + e^-$, and by collisions of electronically excited nitrogen molecules with O_2, $N_2^* + O_2 \rightarrow N_2 + O + O$. In the end, a large amount of OH radicals are thus formed through the chain initiation, $O + CH_4 \rightarrow CH_3 + OH$, and branching reaction, such as $O_2 + CH_3 \rightarrow OH + CH_2O$, $O + CH_2O \rightarrow OH + HCO$. It should be noted in Figure 3 (a) that the corresponding spectrum intensity of electronically excited N_2 are stronger than the OH radicals which means a significant fraction of the electron energy is spent on the excitation of the N_2. These spectrum results indicate that most electrons lose their energy due to relaxation of energetic plasma electrons with nitrogen molecules N_2 and cause the increase of gas temperature. Therefore, the OH formation in the plasma discharge zone mainly lies in the quench of the electronically excited states of N_2.

Figure 3 (b) is the optical emission spectrum in plasma discharge when N_2 is replaced by Ar under the same condition. The spectra have the typical features of an atmospheric argon microwave plasma, which has strong emissions from OH and H electronic bands and strong Ar lines. It is important to note that the OH radical has the strongest intensity in Figure 3 (b), therefore, the OH radical formation in this case is not mainly coming from the quench of the electronically excited states of Ar, but from the plasma initiated methane fuel oxidation and ignition reactions by electron directly impact. According to the results of optical emission spectrum, the flame enhancement by applying an non-equilibrium plasma is more efficient when the dilution inert N_2 in the oxidizer stream (air) is replaced by Ar.

4 Conclusions

In this research, a novel centralized microwave jet burner system is proposed that can be used as a test platform to enable direct studies of PAC under various operation conditions and combustible mixtures. Spectroscopic characterizations of the burner have been conducted using digital imaging and optical emission spectrum. PAC of premixed methane/O_2/N_2 and methane/O_2/Ar mixtures have been investigated at different fuel equivalence ratios and various microwave power. The continuous microwave plasma jets are generated successfully by the design of centralized microwave burner with a sharp-tip electrode as an antenna. The optical emission spectrum results show that with the initiation of a plasma flame by microwave, emission intensity peaks of the OH ($A^2\Sigma^+$) radicals can be observed both in the methane/O_2/N_2 and methane/O_2/Ar mixtures. A comparison of the OH ($A^2\Sigma^+$) emission intensity profile shows that the intensity of OH radical in methane/O_2/Ar mixtures is three orders of magnitude larger than that in methane/O_2/N_2 mixture. Namely, the flame enhancement by applying an non-equilibrium plasma is more efficient when the dilution inert N_2 in the oxidizer stream (air) is replaced by Ar. The coupling efficiency of the dilution inert in the oxidizer stream plays an important role in the flame enhancement mechanism for the PAC system.

5 Figures

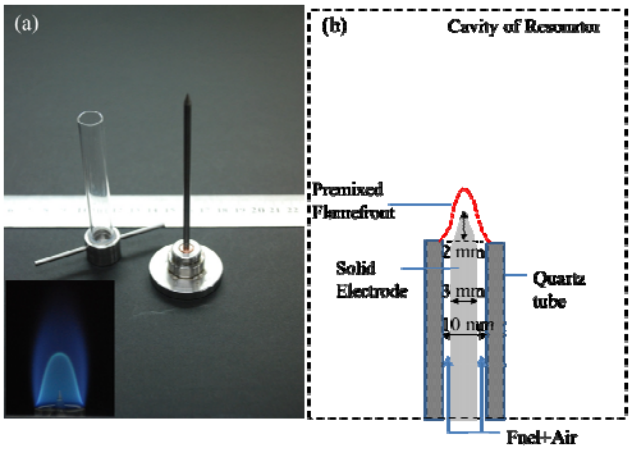

Figure 1. Schematic of the centralized-microwave jet burner: (a) photograph of the burner along with an insert picture of a methane/air premixed flame (b) the corresponding schematic

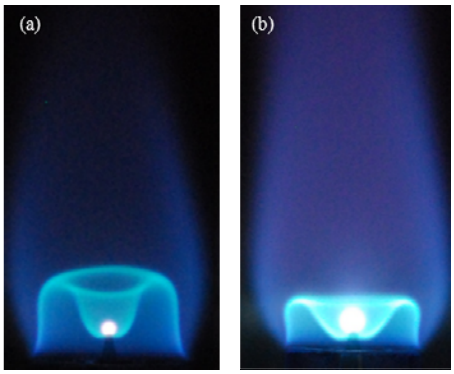

Figure 2. Flame shape with microwave energy of 100W under the same condition of equivalence ratio Φ=1.5 (a) CH_4+(20%O_2/79%N_2) mixture and (b) CH_4+(20%O_2/79%Ar) mixture

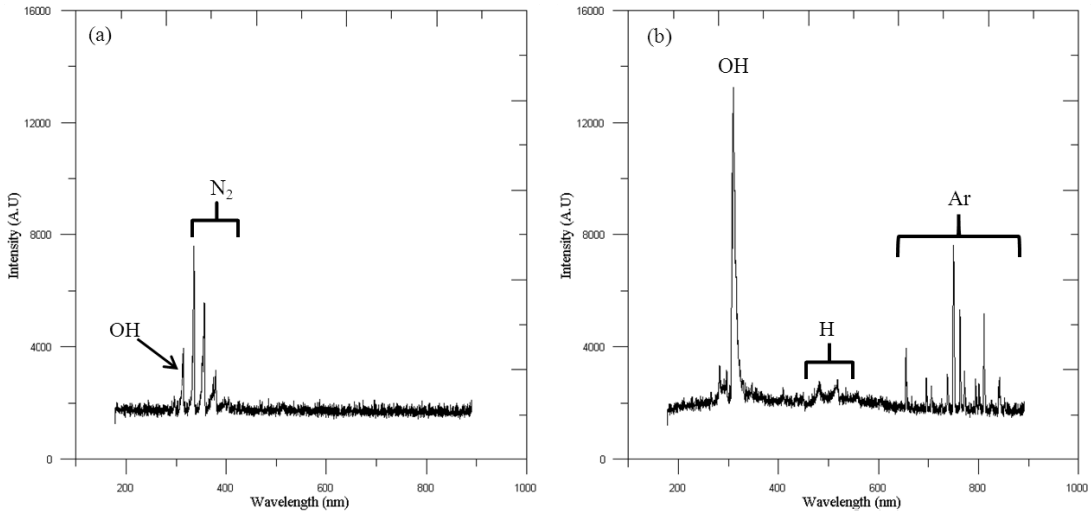

Figure 3. Optical emission spectrum of plasma discharge (a) CH_4+(20%O_2/79%N_2) (b) CH_4+(20%O_2/79%Ar)

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