Study of the Thermal Effects of Microwave induced Plasma on Premixed Methane-Air Flames

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1 Introduction

Recently, atmospheric-pressure microwave plasma sources have found many specific applications in different scientific sectors and specific outstanding applications are recently explored in the field of combustion. Plasma-assisted combustion is particularly well suited for use in challenging conditions where complete and stable combustion is exceedingly difficult to achieve using traditional methods. Several studies have recently shown that application of nanosecond pulsed plasma to hydrocarbon combustion significantly increases the stability of premixed flames [1–6]. In these studies, plasma has been used either to reduce the ignition delay time (IDT) or to extend the lean flammability limit (LFL) as an evidence of flame stability enhancement resulting from plasma discharge. The reaction zone of a flame is thin layer of rapid, non-equilibrium chain reactions and the flame structure is governed by chemical kinetics and flow interactions. In hydrocarbon flames, complex reactions usually also generate 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 enhance and help stabilize the flame in the lean premixed region. The methane-air microwave flame experiments (200-500 W) by Ogawa et al. [7] showed that electron temperature linearly increased with microwave field. A recent experiment and numerical simulation [8-9] on microwave assisted combustion using high power (2-4 kW) in a high Q microwave resonator demonstrated that the flame speed of lean methane-air mixture increased by approximately 30%. In these experiments conducted, supplying of microwave energy is extremely too high compared to the power output from the flame and only insignificant percentage is absorbed into the thin flame region due to the relatively low concentration of ionized species in the flame. The efficiency of combustion enhancement is critical in the assessment of such a system for practical implementations. In Hemawan et al.'s work [12], they have investigated the use of 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. Although the above studies have successfully demonstrated the effectiveness of plasma in combustion, it would be difficult to separate a flame speed enhancement either from plasma or microwave for fundamental flame studies. In addition, due to the large variation of plasma properties and complicated interactions between

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plasma, combustion chemistry, and transport processes, it is even more difficult to understand the mechanism of plasma assisted combustion enhancement, whether the observed enhancement is simply due to the thermal effect or favorably by the chemical effect. Therefore, design of well-defined experimental platforms with isolated enhancement pathways is extremely important to understand the enhancement mechanism and process of plasma. In order to clearly distinguish the interaction between the flame and microwave induced plasma for further studies the flame enhancement process of the microwave/plasma, a novel low-power microwave/plasma burner system is proposed in this study that further concentrates the microwave energy and enhances the absorption of microwave energy by the flame with easy optical accessibility for experiments.

2 Experimental apparatus

A unique concentrated-microwave jet burner is proposed and developed for coupling microwave energy directly into the reaction zone of the flame. A detailed description of this design had been given in our previous study [13] and will only be briefly summarized here. The details regarding this burner are given in Fig. 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. In this experiment, the microwave excitation frequency is 2.45 GHz, and the cavity is excited in the TEM rectangular wave mode. The whole system includes the following 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 found wherein most of the energy is focused on the tip of electrode.

3 Results and Discussions

3.1 Microwave Induced Plasma

With sufficiently strong imposed microwave electric field, a microwave induced plasma can be generated on the sharp tip of electrode. After ignition, the plasma discharge can be maintained stable with a power even less than 50 W and the plasma will further modify the combustion process as shown in Fig. 3. Figure 2 shows the flame shape with plasma discharge for microwave power ranging from 40W to 70W, with fixed air/fuel flow rates of 1.05/0.175 SLM. The sharp-tip electrode configuration adjacent to the flame of the proposed microwave induced plasma burner setup presented here can significantly reduce the power required to ignite and maintain the plasma as compared to the without-flame case and can facilitate convenient experimental accessibility that allows the study of a direct-coupled plasma-enhanced flame with the flexibility for further optical diagnostics of the detailed characteristic flame structure and flame enhancement mechanism. The production of profound radicals and strong gas heating by the plasma discharge ahead of the flame front can significantly enhance the flame velocity and reduce the flame height. The progression of the flame enhancement by microwave-plasma with the input microwave power can be divided into three distinct stages, which are Stage 1: Microwave enhanced stage without plasma ignition, Stage 2: Thermal enhanced stage and Stage 3: Plasma assisted stage respectively. In microwave enhanced stage, the input microwave power is below 40W and the flame is influenced only by a weak electric field. No significant visual change can be observed in either the height or the luminosity of the flame as the power is increased. During the thermal enhanced stage (between 45W and 55W), with plasma ignition the plasma discharge and flame co-exist, and the thermal effect of plasma was manifested by a change in flame tip position. If microwave input exceeds 60 W, the system enters plasma assisted stage where the plasma discharge dominates over the flame and the flame shape is seen dramatically distorted. As the power is further raised, the plasma volumetric discharge is increased.

3.2 Thermal effect of Flame Enhancement by Plasma Discharge

As shown in Fig. 2, with the onset of plasma induced by microwave, a significant flame enhancement can be observed. The flame tip height is decreased dramatically and the enhancement process and mechanism of the methane-air flame by microwave-plasma is further discussed. Because the laminar methane-air Bunsen flames conducted in this study is axisymmetric, the flame tip, usually located in the central axisymmetric vertex point of the flame, can be assumed as a locally flat flame which is very sensitive to change in burning velocity. The discussions on the effects of strain rate and curvature are not the major points of this study and we have reduced the discussion to a minimum. The thermal effect of plasma was observed by a change in flame tip position, with an increase in burning velocity causing the flame to restabilize closer to the burner as shown in Fig. 3. Because flame tip displacement is a sensitive direct indicator of an increase in flame speed, flame tip displacement is plotted versus input microwave power in Fig. 4. Measurements were made in the central portion of the flame. In general, flame tip displacement increased with increases in microwave power. The displacement gradually increased from 2.15 to 2.98 mm when the microwave power is ranging 40-55 W which is stated as Stage 2 before. As the microwave power is above 60W, the displacement dramatically increased from 2.98 to 6.4 mm and finally anchored at the position of the plasma discharge. A parameter that is more directly related to an absolute change in burning velocity is the decrease in fuel flow rate or the increase in air flow rate to decrease the equivalence ratio (Φ) to produce the same flame tip displacement as did the plasma. This percentage change fuel flow and air flow versus input microwave energy is given in Fig.5. The fuel flow and air flow changes were analyzed to estimate increases in burning velocity and the corresponding increase under different unburnt gas temperature obtained by using PRIMIX code are summarized in Table 1. The measured changes in fuel flow and air flow indicate approximately the same changes in burning velocity. The results indicated that the flame speed were increased on the order of 28 to 49 % and the corresponding preheat temperature is ranging from 340 to 390 K. It seems that the observed burning velocity increase can be explained by increase of unburnt gas temperature which means the measured enhancement in burning velocity probably results from simple plasma heating of the unburnt mixtures, and not necessarily from enhancement of a chemical effect. When the microwave power is less than 55W, the radicals in the discharge stream dissipate and disappear promptly to form a stream of stable intermediate specie after dissipation and recombination collisions with neutral and stable species when the radicals moves out of the plasma region. In this stage, only relatively stable radicals and intermediates can reach the region of intense reactions in the flame front, while the short-lived components, with lifetimes shorter than the transport time, will not directly involves in the combustion enhancement. Therefore, in Stage 2, the primary enhancement of the flame comes from the gas heating behind the plasma discharge as mentioned before related to “Thermal enhanced stage”.

4 Conclusions

In this study, a novel centralized microwave jet burner system is proposed for fundamental studies of the flame-microwave/plasma interaction characteristics and flame enhancement mechanism of the microwave induced plasma flames. At low microwave powers, the flame is influenced only by an electromagnetic field. When power is increased, ionization and eventually breakdown of gas molecules result in a plasma discharge sitting on the top of the electrode. Depending upon the input microwave power, three enhanced stages can be categorized. In first stage “microwave enhanced stage” where microwave energy is low and only the microwave electric field couples to the flame with slight increase in flame speed due to electron heating. As microwave power is increased, a plasma source is initiated and the flame-microwave interaction process turns into the “Thermal enhanced stage”. In this stage, the primary enhancement of the flame comes from gas heating behind plasma discharge. Further increasing the microwave power, the flame reaction zone is directly connected to the plasma region, referred as the “Plasma assisted stage”. In this stage, the plasma discharge can ionize methane/air mixture to reactive radicals to further enhance combustion by initiating multiple complex chemical chain reactions.

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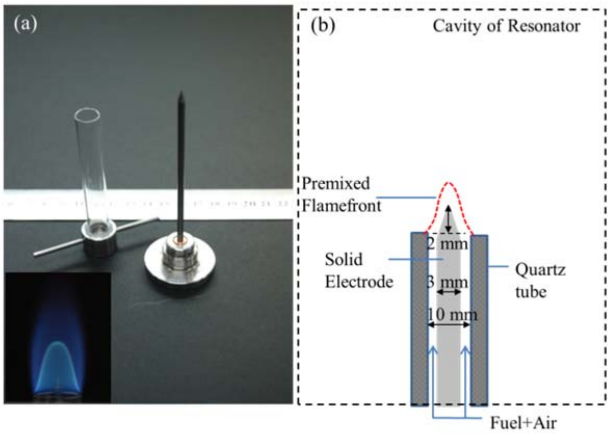

Fig. 1. Schematic of the centralized-microwave jet burner: (a) photograph of the burner along with an insert picture of a methane/air premixed flame (b) the corresponding schematic

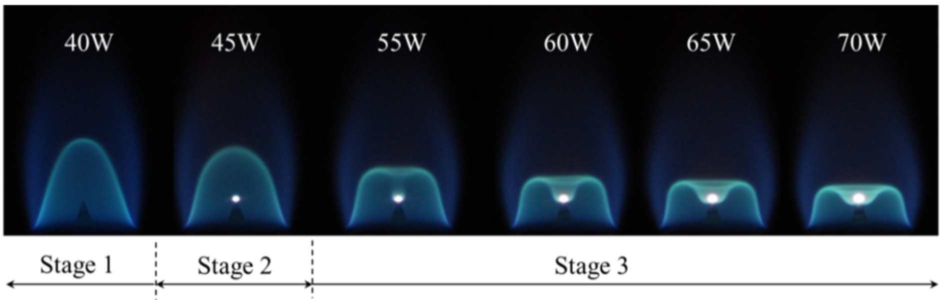

Fig. 2. Flame shape with plasma discharge as the microwave power levels ranging from 40 W to 90 W with three stages noted

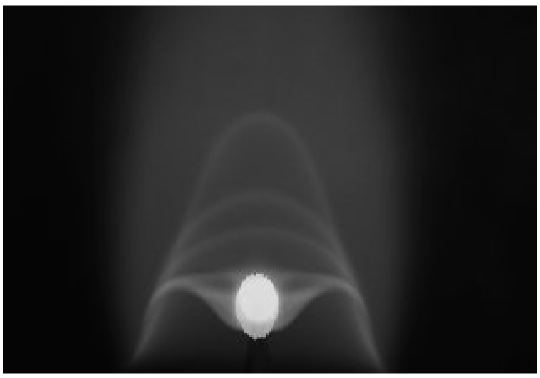

Fig 3. Overlay images of methane/air premixed flame showing flame tip displacement under various input microwave power

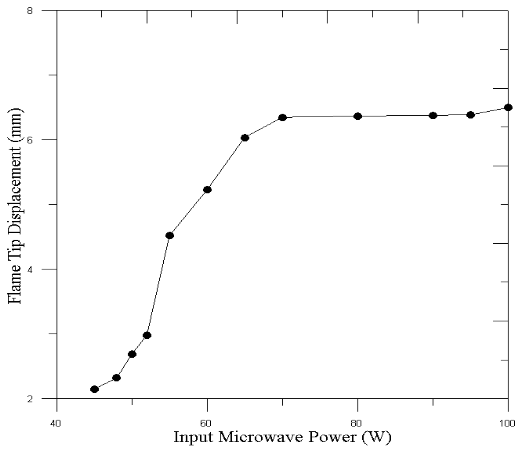

Fig. 4. Flame tip displacement of methane-air premixed flame versus input microwave power

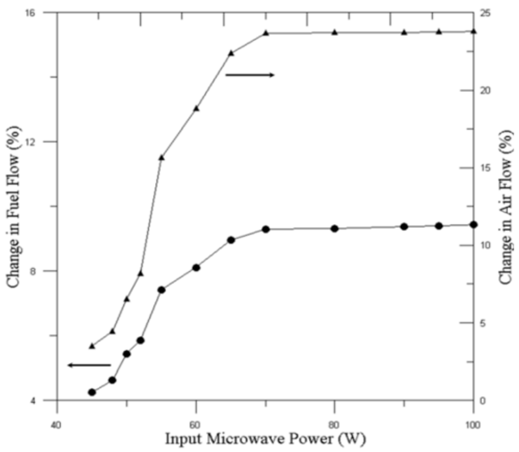

Fig. 5. Percentage change in fuel flow and air flow versus input microwave power for methane-air premixed flame

Input microwave power (W)	%S	Corresponding unburnt mixtures temperature (K)
45	27.90	340
50	35.83	356
55	48.79	385

Table 1 Percentage increases in burning velocity for methane-air premixed flames