Measurements of Hydrocarbon Flame Speed Enhancement in High-Q Microwave Cavity

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In this work we demonstrate that a small amount of microwave power below its breakdown threshold can be locally absorbed into a flame combustion zone. The absorbed microwave power can significantly change the flame speed of both laminar and turbulent flames. PIV technique was employed to measure the laminar flame speed. It was found that microwave assisted flame speed enhancement was greatly dependent on Q of the microwave cavity. Due to the unsteady nature of interaction, microwave assisted flame speed measurements were difficult to make, however, preliminary observations of the flame luminosity indicated that there was energy addition occurring without microwave breakdown and the flame speed was increased.

I. Introduction

Recent theoretical and experimental work at Princeton has revealed that microwave energy can be used to increase the speed of premixed laminar flames1,2,3. This approach, if successful, can play a significant role in the development of high-speed combustors for ram/scramjet engines where long autoignition delay time and low lateral flame propagation speed are among the two key design issues. Other conventional approaches including thermal ignition (laser sparks etc.) and plasma assisted combustion, all require large amounts of power to be deposited in the flow which makes microwave-assisted flame speed enhancement an attractive possible technique to resolve high-speed combustion problems.

Previous experiments indicate that the speed of hydrocarbon flames can be increased by applying DC, AC, or RF electric fields across the flame at atmospheric pressures4. A 25% increase in the methane-air flame speed was reported when an electric field of 440 V/cm (5MHz) was applied5. Work of Clements5 revealed that intense electric fields (~10^7 V/m) capable of producing gas break down behind the flame front did result in 40% enhancement in the flame speed. Fields just below the gas breakdown threshold produced a smaller enhancement (~20% for ethylene and <10% for propane flames). MacLatchy6 investigated microwave (2.45 GHz) effects on premixed flames (equivalence ratios between 0.6 and 0.8) and reported only 6% increase in the burning velocity of the lifted (stand-off distance about 15 mm) flame.

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The previous work on microwave assisted flame speed enhancement at Princeton showed that the flame speed propagation strongly on the microwave power absorbed, and that better performance can be achieved with a high Q microwave cavity\textsuperscript{2}. The work presented in this paper is an extension of the previous investigation and includes new results obtained in a high Q cavity where a particle image velocimetry (PIV) technique was employed to obtain flame speed enhancement in a premixed laminar methane/air flame at various equivalence ratios. The results obtained will assist to understand the microwave-flame interaction phenomenon. How the microwave-flame interaction causes flame speed enhancement is a complicated question which requires further investigation. It has been argued that microwaves heat the electrons in the flame and the hot electrons transfer energy to the reacting species\textsuperscript{7}. It is important to note that all previously reported work on microwave based flame speed enhancement concentrates on premixed laminar flames. Literature on microwave based turbulent flame speed enhancement is very rare. In the current work, very preliminary results on the effects of microwave speed enhancement on turbulent premixed flame are reported. For this purpose, a turbulent burner was designed to fit into a high-Q microwave cavity. A premixed methane/air turbulent flame was produced in the cavity to observe the effects of subcritical microwave field inside the cavity. Initial results are encouraging and are presented in the following sections which also include detailed information on various experiments performed at different operating conditions.

II. Experimental Hardware

a. Laminar and Turbulent Burners

A flat flame burner shown in Figure 1 was designed and fabricated to produce a flat laminar flame at a up to several exit diameters off the burner by arranging for the premixed gas flow to impinge on a flat stagnation plate located approximately 2" from the burner exit. The flat flame was steady and free of large scale fluctuations. The premixed gases entered through the central inlet and passed through a contoured nozzle which was designed to produce a laminar flow. Momentum matched nitrogen entered into an annular plenum through four inlets outside of the premixed nozzle. This plenum led to an annular contoured nozzle which surrounded the inner nozzle. This arrangement produced a laminar central core of premixed gas which was surrounded by a laminar shroud of nitrogen gas. A flat flame was produced by controlling the relative flow rates of the premixed gas and the nitrogen shroud. The stagnation plate was placed above the flow to produce a flat flame structure. The lower two thirds of the premixed nozzle plenum section were filled with 1/8" diameter glass beads, which helped to evenly distribute the flow. This produced a very uniform velocity profile at the exit plane of the nozzle which subsequently produced a very steady flat flame. Through control of various operating parameters – primarily fuel/oxidizer ratio, flow velocity, and separation between the nozzle exit and the stagnation plate – it was possible to control the amount of turbulence in the flame sheet as well as the standoff distance from both the nozzle exit and the stagnation plate.

In order to investigate the effects of microwaves on the speed of a turbulent flame, a turbulent burner shown in Figure 2 was designed. Premixed air and methane mixture entered into a central tube of 0.811 inch diameter. For the operating conditions used in this experiment (Re\textasciitilde3500), a sonic nozzle was used to control the flow rate (~50 l/min) of the premixed gases. The turbulent flame was stabilized with a hydrogen pilot flame by introduced through a concentric nozzle around the main tube, Figure 2. The lower part of the burner was heated to avoid condensation at the nozzle exit.

b. Microwave Cavities

Experiments in this work were conducted in two different microwave cavities. The first cavity was a low Q resonant cavity which consisted of a WR-430 rectangular waveguide as is shown in Figure 3. The cavity was used for high power microwave transmission at 2.45 GHz. At one end of the cavity was a sliding short, and at the other end was a three-stub tuner which acted as a partially reflecting wall. The microwave power was produced by a magnetron which could provide continuous power from 1300 W up to 4500 W. The sliding short was used to control the location of the standing wave such that a field maximum is coincident with the location of the laminar flame burner. The field maximum is stationary in position but switches field direction at a frequency of 2.45 GHz. The three-stub tuner also served as a means to match the phase of the incident wave with that of the standing wave and served as the second
reflecting surface in the cavity. The resonance response was characterized by an increase in the magnitude of the electric field within the cavity. This effect was monitored by placing within the cavity a small coaxial antenna which was connected to a microwave power meter. The resonant cavity used in this experiment operated in the TE_{1,0,10} mode. The maximum electric field produced in this cavity was estimated. It was found that for a power level of 4500 W, a electric field of about $2 \times 10^5$ V/m was achieved in the cavity. The Q of this cavity was very low and was measured around 5. Further details of this cavity have been presented in reference 1.

The second cavity, shown in Figure 4, was specially designed and machined to achieve a high Q condition. This cavity was also formed from a section of WR430 waveguide and it retained these physical dimensions of the low Q cavity. The cavity has four of the six walls machined out of a single block of metal, thereby reducing the number of locations where the electric field pattern could be distorted. Power was coupled into the cavity using a coaxial antenna. The antenna termination inside the cavity was designed so as to allow both high power operation and to reduce the possibility of creating a standing wave in either the rectangular waveguide to coaxial cable transition or the preceding microwave transmission line. While the resonant electric-field pattern was slightly distorted in the region surrounding the antenna, the TE_{105} mode was well established in approximately half a guide wavelength. The burner was located more than this one-half guide wavelength away from the coupling antenna in a region of maximum electric field. The incorporation of a precision sliding short allowed for fine tuning of the cavity resonance. The quality or “Q” of the cavity was experimentally determined using a low power sweep generator. The sweep generator was used to introduce low power microwave energy into the microwave transmission line and the frequency of this microwave energy was then be “swept” through a range of frequencies which included the resonant frequency of the cavity. At resonance, Q was determined by dividing the resonant frequency (2.45 GHz) by the FWHM of the resonant peak. Experimental results suggested a Q of around 1000 for this cavity.

c. PIV Accessories

c1. Seeder

In particle image velocimetry (PIV), an indirect measurement of the flow field is made by measuring the velocity of the tracer particles. Micron size seeding is required so that the particles can follow the flow. The technique relies on collecting the light scattered by the tracer particles. The light scattering characteristics of the particles can be described by Mie theory. It strongly depends on the size of the particle, polarization orientation, direction of observation, and aperture size. The combined result of Lorentz-Mie theory with specific considerations to PIV applications, in which the scattered light is observed at 90° from the incident light and in which the light sheet is a Gaussian profile, was calculated by Ren. They showed that the light intensity scattered by the particles does not change much with the size from 1 to 10 microns, and that in order to obtain uniform particle images, the size must be less than 10 microns. For the microwave work conducted in this experiment, an additional requirement for these particles was that they should be non-conducting, non-toxic, non-corrosive, non-abrasive, non-volatile, chemically inert, and have a high melting temperature. Boron nitride powder (.1-1.0 micron diameter) was used to conduct PIV work in these experiments. One problem with Boron Nitride particles is that they have a tendency to agglomerate to produce large size particles. To avoid this problem, a seeder, shown in Figure 5, was designed where the solid particles cloud was generated through a fluidized, cyclone aerosol generator which was controlled by a magnetic stirrer. The agglomeration was avoided by heating the fluidized bed whereas the particle concentration in the inlet air was controlled by the rotating speed of the stir bar through a Synbon magnetic plate.

c2. PIV Laser and Image Acquisition

A Spectra Physics 400 M, double cavity, Nd:YAG laser was used to produce two laser pulses (10 ns width and 10 Hz repetition rate). A cylindrical lens was used to create laser sheet (0.5 mm thickness) in the microwave cavity at the flame position. A Stanford Research Systems timing box was used to trigger the lasers and to control the time separation between the two laser pulses. For the work reported here, the time separation between the pulses was maintained in a range of 800 to 1000 µs. The shutter speed of the camera was set according to the frequency of the double pulses to guarantee that only one pulse sequence
illuminates the flow field when the shutter is open. A Kodak DCS 460 digital camera with resolution of 3060×2036 pixels was use to capture the flow field in the microwave cavity. The camera was equipped with a narrow band filter with a bandwidth of 60 nm to filter out the flame radiation and pass most of the laser light near 532 nm. The recorded images were subsequently analyzed using an in-house auto-correlation code. The PIV code utilized self-optimizing FFT algorithms, variable interrogation window size, and subpixel peak detection techniques. The code was designed to include algorithms for automatic interrogation peak selection/rejection as well as stretch rate/reference flame speed determination. Further details on the PIV Code are provided in reference 11.

III. Experimental Results and Discussion

As the work presented in this paper is a continuation of the previous work, only a few of the results from the references 1 and 2 will be added here for the sake of continuity. Figure 6 shows the results for the methane-air flame obtained in a low Q cavity with the operating conditions described below:

| Mass flow rate | 5744 st. cm³/min |
| Exit velocity | 54 cm/s |
| Equivalence ratio | 0.70 |

As the microwave power was applied, the steady methane-air flame moved upstream toward the burner, thereby indicating the increase in its propagation speed. The flame came back to its original position after the microwave power was turned off. Figure 6 is a series of photographs showing the flame (methane-air) position as a function of input microwave power. The flame occupied a roughly circular volume with a diameter of 1.7 cm and a thickness of 0.4 cm. As the microwave power level was increased from 0 to 2600 W, the flame clearly moved down towards the burner exit and against the flow of the fuel/air jet towards the burner exit. The velocity of the outer annular nitrogen was matched with the fuel/air jet to prevent entrainment of the surrounding air. The flow data and the burner/waveguide geometry were used as input to a finite-element model for the solution of the steady state flow field presented in the confined region above the burner exit. The model was solved using the commercial program FEMLAB, the details of which have been included in reference 1. From the model percentage increase in the flame speed at various microwave power levels was obtained and is shown in Figure 7. The maximum observed increase in the flame speed based on the experimental results interpreted by the model was 68% as the microwave input power was increased to 2600 W. Keeping in view the 2-D and other assumptions made in the FEMLAB model, the 68% increase in the flame speed only presented a rough estimation of the flame speeds and was used as a first hand guess on the microwave impact on the flame propagation speed.

Experimental results from the high Q cavity are shown in Figure 8. These results were obtained for air/methane flame with the following operating conditions:

| Mass flow rate | 5725.56 st. cm³/min |
| Exit velocity | 44 cm/s |
| Equivalence ratio | 0.77 |

In this case a continuous 1kW microwave source at 2.45 GHz provided microwave power to the cavity. Again the trend is similar to that observed in figure 6. As the microwave power is increased, a corresponding increase in the flame propagation speed occurs similar to that which can be seen in figure 6. One remarkable difference between results presented in figures 6 and 8 is that in the case of the high Q cavity, very low microwave power is required to observe a change in the flame propagation speed i.e. on the order of few hundreds of watts as compared to kilowatts in the case of low Q cavity. The percentage increase in the flame propagation speed was again estimated by two different approaches. The first was to keep the microwave power constant at 403.32 W (position 5 in Figure 8) and then increase the exit velocity to bring the flame position back to the zero microwave power position (position 1 in Figure 8). The nitrogen flow was also increased to match the flow conditions through out this experiment. The assumption then is that the percentage increase in the jet exit velocity required to return the flame to the original zero power position is the same as the percent increase in the flame speed caused by the microwave. This approach gave a flame speed increase of 21%. It will be important to note that 21% increase was estimated in a high Q cavity where the incoming microwave power was only 400 W as compare to 2.6 kW in a low
Q cavity where 68% increase in the flame velocity was estimated. This comparison clearly shows the impact of high Q on the microwave assisted flame speed enhancement.

Another important aspect of the experiment was to find out the absorbed power by the flame as the microwave power was increased from 0 to 403.32 W as shown in Figure 8. The absorbed power was measured from the reflected power with and without the microwaves at fixed flame positions and with fixed operating conditions i.e. the Q of the cavity, the gas exit velocity, and the equivalence ratio. Figure 9 describes the results. It is clear that the power absorbed by the flame increases as the forward microwave power is increased from zero to 403.32 W. Measurements show that maximum power of 20 W is absorbed by the flame as the input forward power reaches around 400 W (position 5 in Figure 8). Indeed, for the 2 cm diameter flame just described, theoretical estimations reveal that the absorbed power does not exceed 22 W which is very close to the experimental observation.

In order to verify the above results, direct PIV measurements were made in the high Q cavity. Figure 10 shows a typical PIV result for a given flame position. For the shown flame parameters it is clear that the PIV technique was able to provide a velocity profile that gives the flow speed at the flame front to be about 32.58 cm/s. This result was obtained for an air/methane flame with an equivalence ratio of .78 without any microwave power in the cavity. Three PIV images showing the impact of microwave power are shown in Figure 11. These PIV results indicated that the stretched flame speed increased from 33.7 cm/s to 45.3 cm/s as the microwave power was increased up to 1.2 kW. An equivalence ratio of 0.78 was kept constant in these experiments. Figure 12 shows PIV velocity profiles at three microwave power levels (0, 700 W, 1200 W). Corresponding percentage increase in the flame speed is shown in Figure 13. At 1.2kW microwave power level, the corresponding percentage increase in the flame speed is about 34.5%. Experimental results in Figure 13 also verify that the previous estimates on flame speed enhancement were not that far off:

<table>
<thead>
<tr>
<th>Air/Methane flame</th>
<th>Microwave power</th>
<th>Cavity</th>
<th>% increase (flame speed)</th>
<th>Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalence Ratio</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.77</td>
<td>2.6 kW</td>
<td>Low Q</td>
<td>68%</td>
<td>Estimated – Indirect method</td>
</tr>
<tr>
<td>0.77</td>
<td>403 W</td>
<td>High Q</td>
<td>21%</td>
<td>Estimated – Indirect method</td>
</tr>
<tr>
<td>0.78</td>
<td>1.2 kW</td>
<td>High Q</td>
<td>34.5%</td>
<td>PIV – direct method</td>
</tr>
<tr>
<td>0.74</td>
<td>1.2 kW</td>
<td>High Q</td>
<td>28.28%</td>
<td>PIV-direct method</td>
</tr>
</tbody>
</table>

Figure 12 also shows results at various equivalence ratios (0.74, 0.76, 0.78) and reveals that flame speed enhancement depends on both the equivalence ratio and the incident microwave power. In these experiments, the microwave field strength in the resonator cavity was below that required to initiate or even sustain a plasma without the flame. Since microwave absorption in the neutral gas molecules was negligible, the effect of the field on the burning speed indicated that the microwave field was coupled to the very thin flame front region where the reaction rate peaks, maintaining that coupling as the flame front moves. Some additional coupling may occur in the region behind the flame front due to the presence of residual ions but that appears to be much less than in the flame front. This coupling to the flame front also means that the total microwave power absorbed is quite low. Indeed, the absorbed microwave power was about few Watts for the results shown in Figures 12 and 13.

Experiments were also performed to investigate the impact of microwave power on the combustion speed of a turbulent air/methane flame (Re = 3500 and equivalence ratio = 0.8). The turbulent burner shown in Figure 2 was employed for this purpose. Turbulent flame images were obtained with and without microwave power. Results are shown in Figure 14. The change in luminosity can be clearly seen as the microwave power is turned on. Figure 15 compares the flame luminosity at different regions in the flame with and without the microwave power. In each case a slight increase in flame luminosity can be seen showing the effect of microwaves on the flame structure. In order to estimate the percentage increase in the flame speed, the premixed flame region (which appeared as a cone) was marked and compared. 11.4% increase in the flame speed was estimated as shown in Figure 16. It is important to note that the method to mark the premixed flame cone is not accurate. For a precise work, the species concentration and
flame temperatures should be measured. In that sense the results presented in Figures 15 and 16 are preliminary in nature and merely provide an indication that microwave assisted flame speed enhancement may equally be applicable for turbulent flames.

IV. Conclusions

We have demonstrated that a small amount of microwave power can be locally absorbed into a flame combustion zone without producing uncontrolled microwave breakdown, and that the absorbed microwave power significantly changes the flame speed of both laminar and turbulent flames. The change in flame speed in the laminar flow has been measured using Particle Imaging Velocimetry, which gives results that are consistent with the observed change in flame location and with the observed offsetting effects of a change of the equivalence ratio. The measurements in the turbulent flame are more difficult due to the unsteady nature of the interaction, but preliminary observation of the flame luminosity indicates that there is energy addition occurring without microwave breakdown, and that the flame speed has been increased. Estimates show that the absorbed microwave power is significantly less that the power released by the flame itself. All of these experiments have been carried out in resonant microwave cavities, and in the high Q cavity, effects are observed with powers of less than half of those required in low Q cavities.

Acknowledgments

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References

Figure 1. Two views of the flat-flame burner. A) the plenum with a central inlet for fuel/oxidizer premix and outer inlets for nitrogen, B) central contoured nozzle for premixed jet.

Figure 2. Schematics of the turbulent flame burner

Figure 2. Schematics of the turbulent flame burner
Figure 3. Resonant Cavity A: Schematic diagram of the microwave cavity, standing wave, and the laboratory set up of the experiment.

Figure 4. Resonant Cavity B: Schematic diagram of the high Q microwave cavity, standing wave, aperture plate, and the laboratory set up of the experiment.
Figure 5. Boron Nitride particle delivery system

Figure 6. Sequence of video stills taken in cavity A (low Q cavity). As the microwave power was increased, the flame (methane-air) moved downward against the flow of air/fuel jet towards the burner exit.
Figure 7. Percentage increase in the methane-air flame as a function of the input microwave power.

![Graph showing percentage increase in flame speed vs input power.](image)

Figure 8. Sequence of video stills taken in cavity B (high Q cavity). As the microwave power was increased, the flame (methane-air) moved downward against the flow of air/fuel jet towards the burner exit.

![Sequence of video stills showing flame movement.](image)
Figure 9. Variations in absorbed power by the flame with its positions [marked in figure 8] in the cavity.

Figure 10. Flame speed calculated from auto-correlated PIV calculations along flame centerline
\[ \text{CH}_4/\text{Air} \ v_{\text{exit}} = 85 \ \text{cm/s} \]
\[ \phi = 0.78 \]

Figure 11. PIV images showing the effect of microwave power

Figure 12. PIV results showing microwave assisted flame speed enhancement
Figure 13. PIV measured flame speed enhancement at various equivalence ratios

Figure 14. Luminosity of Turbulent Flame indicating MW Coupling
Figure 15. Luminosity across the turbulent flame with and without microwave power (1500 W)
Figure 16. Preliminary estimates of turbulent flame speed enhancement due to 1500 W microwaves.