Ultraviolet Laser Induced Ignition Using Resonant Enhanced Multiphoton Ionization

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Abstract: A novel resonant laser-induced breakdown scheme has been demonstrated to provide precision spatial guidance of spark formation within an air flow and has been further demonstrated successfully in resonant laser-induced ignition of a moderate-speed flow of an air-propane mixture. This scheme could potentially provide ignition within a combustion system with a laser trigger leading to breakdown of an air-fuel flow within a high-voltage gap using a compact low power laser source. The laser scheme involves resonant enhanced multiphoton ionization (REMPI) in molecular oxygen and subsequent laser field-enhanced electron avalanche to generate a pre-ionized micro-plasma path between high voltage electrodes and thus guide the ignition spark through fuel-rich areas of the air-fuel flow. With this resonant method, sufficient photo-ionization and laser field-enhanced electron avalanche ionization have been generated for inducing air breakdown at a relatively low laser power compared to most laser breakdown concepts. This low power requirement may allow for a laser source to be transmitted to an ignition chamber via fiber optic coupling. Results of this study include high speed photography of flame ignition in an air-propane flow, showing the spatial and temporal evolution of the laser-induced spark and flame kernel leading to combustion.

Keywords: laser induced ignition, combustion, multi-photon ionization, propane

1. Introduction

A variety of methods can be used to initiate breakdown leading to the ignition of an air-fuel mixture within a combustion system. The most common mechanisms to induce ignition is the production of high-tension sparks by conventional induction coils or production of high-energy and very high temperature sparks produced by a condenser discharge. There has been some research and development of laser ignition technology intended for the eventual replacement of spark-plug igniters with laser ignition systems in combustion chambers. Most of this previous work has involved very high power pulsed lasers that cause high-field breakdown of air and photoelectron effects at an electrode surface. The practical issues of gaining optical access to the ignition volume and integrating a high power pulsed laser near a combustion engine has been a concern. An attractive concept is the guidance of a lower power laser pulse via fiber-optic cable into the ignition region that still reliably induces breakdown of the air-fuel mixture. Ignition induced by a fiber coupled laser could possibly be realized by keeping the required laser power low through efficient volume ionization with the laser tuned to the proper wavelength to achieve resonant-enhanced multiphoton ionization (REMPI).

Previous work has shown that a focused laser beam at 287.5 nm created abundant ionization in dry or humid air at atmospheric pressure due to an REMPI transition through molecular oxygen \([1,2]\). In recent experiments, the induced breakdown of a flowing air gap with an applied high voltage was investigated with a focused laser at 287.5 nm \([3]\). This laser technique at 287.5 nm excited a REMPI process in molecular oxygen with an initial 2-photon transition to \(\text{O}_2(\text{C}^2\Pi, v=2)\) state as an intermediate. From the \(\text{O}_2(\text{C})\) state, the third photon within the same laser pulse readily ionizes the \(\text{O}_2\), creating the ions and electrons in the laser focus region. This scheme is termed a 2+1 photon REMPI process and is shown in Figure 1 using a potential energy diagram of molecular oxygen. In the previous experiments in flowing air, two parallel electrodes were configured as an air flow gap and were connected in series with a capacitor charged to several tens of thousands of Volts. A pulsed ultraviolet laser, at a wavelength of 287.5 nm, was propagated co-axially through a small aperture in the anode. The ionization caused by the laser produced a channel of free charge between the electrodes, inducing electron avalanche and generating the arc. Resonant laser-induced breakdown was found to be reliable across an air gap spacing of 5 cm and guided at an angle as high as 40° to the electric field to demon-
strate the practicality and the precision guidance of the technique. Laser-induced breakdown by this method was accomplished with an applied voltage as low as 20% of the voltage required for self breakdown.

The present effort is an extension of the previous work in air to demonstrate that the same laser REMPI technique used to induce breakdown in a pure air flow could also cause breakdown in an atmospheric pressure air-fuel mixture and subsequently lead to ignition of a flame. High speed photography was used to analyze the evolution of the laser induced ionization up through flame ignition.

2. Experimental Set-up

The basic set up for the laser induced flame ignition is shown in Figure 2. The propane-air burner was a surface-mixed glass burner with a 50/50 mix of air/propane, each pressurized to 5 psi. The upward flow was approximately 20 m/s through the ignition region. The flow was directed between two electrodes with variable interelectrode gap spacing which was set to a 3 cm spacing for these experiments. The thicker anode represented an insulated high voltage electrode that in an operational application would feed through into the ignition chamber and the ground electrode would be the opposite wall of the chamber. The anode had a 2 mm hollow aperture to allow the laser to propagate into the interelectrode gap. The high voltage circuit required to energize the ignition gap included a charging circuit consisting of a 100 kV variable DC voltage supply, a 1 MΩ resistor and three 2.2 nF capacitors in series which gave a charging time constant of slightly less than 1 ms. Once charged, the capacitor could be discharged through a circuit that was switched by the ignition arc within the gap and included a 0.5 MΩ load resistor which limited the discharged current. For these experiments, a voltage of 30 kV was applied which represented a field of 10 kV/cm. Such an applied field was chosen since it initially would not cause self-breakdown, but was known to be sufficient to allow pulsed laser-induced breakdown of air [3]. Thus, breakdown and ignition could be reliably controlled by the laser pulse.

A dye laser system was used to induce breakdown in the air-propane flow. The second harmonic output of a Nd:YAG laser pumped rhodamine 590 dye was frequency doubled in a SHG crystal, producing a wavelength of 287.5 nm to match the \( \text{O}_2(X^2\Sigma^+ v=0 \rightarrow C^3\Pi v=2) \) two photon transition wavelength. The laser was then passed through a lens of focal length \( f=15 \text{ cm} \) and focused through the aperture in the anode and into the center of the interelectrode gap, eventually striking the cathode. The laser focal region extended across the gap with a beam waist of 50 \( \mu \text{m} \) and created a continuous channel of high laser energy density between the electrodes. To induce ignition, the laser was operated in single shot mode with pulse energy variable up to about 3 mJ.

High speed imaging of the laser induced ignition event was conducted with a Phantom v7.0 high speed video camera system with a frame rate of 10,000 frames per second. Still images presented in this paper were taken from the high speed video.
3. Results and Discussion

The results presented here on resonant laser-induced ignition of the air-propane burner confirmed that the burner could indeed be ignited reliably under similar conditions where laser-induced breakdown was achieved in a pure air flow. The color photograph shown in Figure 3 depicts the entire laser induced breakdown and flame ignition event over a 125 ms exposure time. The bright white arc of the breakdown across the laser path between electrodes is clearly visible, along with bright blue ignition activity just above the laser and less bright combustion activity further up the plume.

Select results of the high speed imaging are reported here as well. Figure 4 displays the initial short term breakdown events for times of 0, 200, 400, and 600 $\mu$s after the laser pulse. The initial frame labeled 0 $\mu$s in Figure 4 shows a high current arc formed within ~0.1 $\mu$s after the laser that initially followed a relatively thin straight column between the electrodes along the laser ionization path. At 200 $\mu$s, the capacitor circuit had discharged and was recharging, while a dim plasma glow was still visible between the electrodes and was drifting upward with the air-propane flow. At 400 $\mu$s and 600 $\mu$s, secondary arcing from the capacitor circuit occurred with the arc following the plasma column that was drifting upward. The right side of the arc remained attached to the smaller anode while the left side tended to float upward along the grounded electrode.

The images in Figure 5 show a more extended time frame of the breakdown to the flame evolution. The images start at 0.5 ms after the laser pulse and continue to 6.5 ms in steps of 1 ms. An interesting dynamic in Figure 5 was how disperse plasmas formed near each electrode in the later images and new arcs jumped between these plasma (obviously at different potentials) after the initial arc column had drifted above this region at times > 2.5 ms.

Figure 3. Color photograph with 125 ms exposure of laser induced ignition event with in propane-air flow.

Figure 4. High speed camera images of initial breakdown in laser induced ignition of propane-air flame.
A notable observation in these experiments was that the presence of propane in the air did not hinder the initial photo-ionization and breakdown event. In fact, there was some evidence that the propane mixture enhanced the overall photo-ionization and breakdown process, albeit through some different mechanism besides REMPI of molecular oxygen. The evidence showed that laser-induced breakdown would occur reliably for 100% of laser shots at 287.5 nm for both air and air-propane at 10 kV/cm, while at 282.5 nm, the laser would never cause breakdown in air, but would occasionally cause ignition in the air-propane flow (30% of the time). This indicated that some non-resonant photo-ionization process may be occurring in propane that rivaled the oxygen REMPI. The images in Figure 6 also show a fundamental difference in the shape of initial breakdown along the 287.5 nm laser ionization path between the case of air only and a air-propane mixture. The glow distribution in the air only case appears to indicate a fairly homogeneous spread of photo-ionization extending from the anode, whereas the air-propane case appear to have an intense arc spot less than 1 cm from the anode.

4. Conclusion

This study demonstrated that a low power laser REMPI technique involving molecular oxygen could be applied successfully to induce breakdown in an atmospheric pressure air-fuel mixture and subsequently lead to ignition of a flame. Future studies are planned to determine whether the noticeable difference in air-propane arc formation was a photo-ionization effect in propane or alternatively an effect of the propane on the avalanche breakdown process after the initial oxygen REMPI event.

Acknowledgement

This work was supported by the Air Force Office of Scientific Research

References