82 KSME International Journal, Vol. 13, No. 1, pp. 82~89, 1999

An Experiment on the Combustion Characteristics with Laser-Induced Spark Ignition

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(Received January 13, 1998)

The combustion characteristics and minimum ignition energies using laser-induced spark ignition were demonstrated for quiescent methane-air mixtures in an optically-accessible, constant volume combustion chamber. Initial pressure and equivalence ratio as well as spark energy were varied in order to explore the flame behavior with laser-induced spark ignition. Shadowgraphs for the early stages of combustion process showed that the flame kernel becomes separated into two, one of which grows back towards the laser source. Eventually after a short period, the two flame kernels developed into two flame fronts propagating individually, which is unique in laser-induced spark ignition. For a given mixture, lower initial mixture pressure and higher spark energy resulted in shorter flame initiation period and faster flame propagation. The results of minimum ignition energies for laser ignition shows higher values than electric discharge results, however, the difference decreases toward lean and rich flammability limits.

Key Words: Laser-Induced Ignition, Flame Kernel, Minimum Ignition Energy (MIE), Combustion Duration.

1. Introduction

Lean burn system has been regarded as an alternative approach that could improve thermal efficiency while reducing exhaust gas emissions such as nitrogen oxides, carbon monoxide and unburned hydrocarbons. High exhaust gas recirculation engines also have similar potential for emission improvement. Current lean burn engines, however, cannot be operated with sufficiently lean condition because of ignition related problems such as sluggish flame initiation and propagation, and even potential misfiring. Therefore, the development of lean charge associated with fast burn engines requires enhanced ignition capability to compensate low burning speed in lean mixtures. Various ignition systems for internal combustion engines operating with premixed charge has been presented (Dale and Oppenheim, 1981), including high energy spark plugs, plasma jet ignitors, laser ignition, flame jet ignitors, torch jet ignitors, and exhaust gas recirculation ignition systems.

There are a number of unique advantages associated with the use of laser-induced spark ignition for combustible mixtures compared with conventional electrode discharge sources. For example, laser spark is almost a perfect point energy source in which energy and rate of its deposition can be controlled and measured accurately. It also has the ability to choose proper timing and location(s) of ignition which are not easy with conventional ignition systems. Also, the complete absence of material surfaces in the vicinity of ignition region eliminates the complex effects of heat transfer during the initial growth of flame kernel. In addition, the duration of pico- to nano-seconds in many pulsed lasers can be much shorter than most important chemical reaction times. Basically, there are four physical mechanisms by which a laser can produce an ignition kernel; resonant and nonresonant breakdowns, thermal heating and photodissociation. A detailed discussion of various types of laser-in-

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duced ignition can be found elsewhere (Ronny, 1994).

The laser ignition has been successfully tested in a combustion bomb to establish ignition limits for hydrocarbon-air mixtures (Hickling and Smith, 1974), as well as minimum ignition energy studies (Lim, et al., 1995, Syage, et al., 1988). Apparently, only one study in a reciprocating type internal combustion engine has demonstrated the potential benefits of laser ignition. Dale et al. (1978) studied the performance of a single -cylinder internal combustion engine using a pulsed CO_2 laser. They demonstrated that, in comparison with a conventional spark ignition, significantly leaner mixtures could be burned with laser ignition than was possible with electric spark ignition. The power output of engine was increased and carbon monoxide and unburned hydrocarbon emissions were similar for the two ignition systems while nitrogen oxides level was actually increased. However, for a given nitrogen oxides emission level, significantly higher thermal efficiency could be obtained with laser ignition. In spite of merits in laser ignition systems, the application of these devices are restricted to research and development rather applying to actual engines.

The purpose of this study is to examine the effect of laser-induced spark ignition on flame initiation and propagation especially during the early stage of flame propagation, and to measure the minimum ignition energies for different mixtures of CH_4/air. Also, the effect of laser spark energy on parameters affecting combustion such as flame initiation period, combustion time and maximum combustion pressure were examined for quiescent methane-air mixtures using a shadowgraphy and pressure measurements in an optically-accessible, constant volume combustion chamber.

2. Experiment

Experimental apparatus, as schematically shown in Fig. 1, consists of a combustion chamber, a laser ignition system and a visualization setup. The combustion chamber is a hexahedron

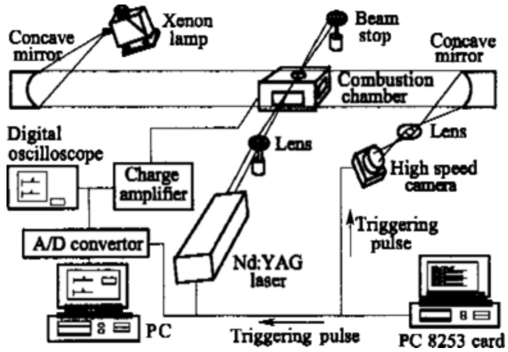

Fig. 1 Schematic diagram of experimental setup.

with the dimension of 60×60×20 mm. It has two glass windows with high power coating which serve as an entrance and an exit for the laser beam and another two quartz windows on the other two sides in order to take schlieren or shadow photographs. Methane and air were premixed in a mixing chamber where their equivalence ratio was determined based on the partial pressures. To assure mixture homogeneity, the mixing chamber was charged at least one hour before use, the mixture was then introduced into the combustion chamber.

A Q-switched Nd:YAG laser (Spectra Physics, GCR-150) was used as ignition source. This laser can produce either a single or multiple pulse, 7-ns pulse duration at 532-nm wavelength with a beam diameter of 7 mm with a maximum available energy per pulse of 360 mJ. In order to focus the laser beam through the window into the combustion chamber, a 100 mm focal length convex lens was used. Instantaneous pressure in the chamber was measured by a piezoelectric pressure transducer (Kistler, 6051; range 0-200 bar) connected to a charge amplifier (Kistler, 5011), a digital oscilloscope and a personal computer. Based on the average of measured pressure traces for three different trials, characteristic values were estimated and analyzed which include flame initiation period, combustion duration, and total combustion duration. Flame initiation period (FIP) is defined as the period when 5% of the mass is burned, t_5; the total combustion duration as the time when 90% of the mass is burned, t_{90}; and the combustion duration for period from

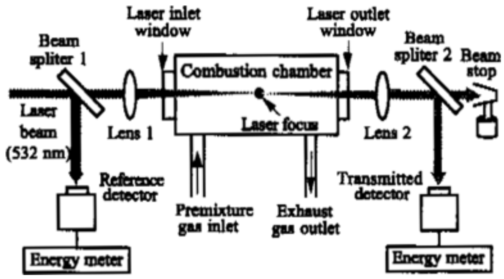

Fig. 2 Schematic of the experimental apparatus showing principle of ignition energy measurement.

5% to 90% mass burned.

A high speed camera (Hitachi, 16 HM; max. 10000 fps) was used to visualize flame behavior inside the combustion chamber. The laser ignition timing and starting times of high speed camera are synchronized.

Ignition energy measurements were made as schematically shown in Fig. 2, using a dual beam arrangement in which two beam splitters located before and after combustion chamber served to reflect a small percentage of the incident and transmitted laser beams onto the respective detectors (Molectron, J25-152). The reference and transmitted pulse energies were measured using a laser energy joulemeter (Molectron EM 500), which in turn were calibrated by a thermopile energy meter (Scientech). Energy losses due to lenses and windows were considered while other losses such as the radiance and the light scattered by the gas breakdown induced plasma were neglected (Syage, et al., 1988). It is to be noted that the fluctuation in incident laser energy is ranged between 3%~4%. A detailed explanation of spark energy measurements can be found elsewhere (Mohamed, et al., 1997). Laser-based minimum ignition energy measurements employed here have two main advantages over classical minimum ignition energy experiments. One is the actual energy deposited in the gas, rather than just the energy stored in a capacitor bank, is measured. The other is there are no electrodes to act as heat sinks.

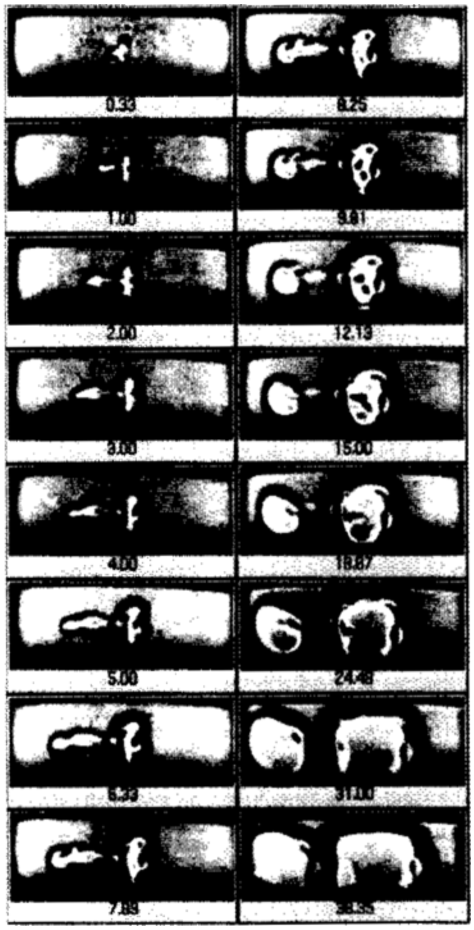

Fig. 3 Shadowgraphs for early stages of combution process for $\phi=0.7$ and $P_i=1.5$ atm. Numbers indicate time in ms after ignition.

3. Results and Discussion

Figure 3 shows the shadowgraphs for the early stage combustion process for mixture at an equivalence ratio of $\phi=0.7$ and initial pressure of $P_i=1.5$ atm. The laser used for ignition enters from the left and is focused at the center of the combustion chamber. Images clearly show that the laser generated flame kernel exhibits elongation along the path of the focused laser beam with nearly separated two kernels (lift and right), one of which grows back towards the origin of ignition laser. Eventually after a short period, the two flame kernels separate into two flame fronts propagating individually. The preferential flame growth back toward the ignition laser has been observed previously in the planar laser induced fluorescence (PLIF) imaging by Seitzman, et al., (1988) for laser-ignited methane/air flames and Spiglanin, et al., (1995) for laser-ignited hydrogen/air flames. Spiglanin, et al., (1995) explained such phenomenon as follow: as soon as the ignition occurs, an initial plasma is formed near the focus of the laser. This plasma rapidly heats up the surrounding gas and ionizes it. The freshly ionized gas on the side facing the laser then is able to absorb the more laser energy and is rapidly heated. Thus the boundary of highly heated plasma rapidly propagates back toward the ignition laser. Another possible contribution to this phenomenon may be due to the shock wave that results from the initial expansion of the flame kernel. The resulting shock wave will then propagate outward but with an axial component away from the intense spark center with the direction facing the incoming laser beam. Gases rushing to fill the hot, over-expanded region then rapidly ignite to form the kernels observed.

The heat release rate was calculated using the following energy equation without considering any heat loss (Amann, 1985; Gatowski, et al., 1984),

$$\frac{dQ}{dt}=\frac{1}{\gamma-1}\ V\frac{dP}{dt}$$

and the net heat release during combustion,

$$Q=\int_0^t\left(\frac{dQ}{dt}\right)dt$$

The mass burned fraction, x, was calculated from the computed heat release history using the following relation,

$$x=\frac{1}{Q_{max}}\int_0^t\left(\frac{dQ}{dt}\right)dt$$

where Q is the net heat release, t is the time, P is the pressure, V is the volume of combustion chamber, γ is the specific heat ratio, and the subscript max indicates the maximum.

The specific heats ratio γ is a function of temperature, pressure, and the equivalence ratio of the mixture and its values were calculated using CHEMKIN-Ⅱ (Kee, et al., 1989). The temperature used to evaluate γ was the mass average temperature calculated from the ideal gas law (Gatowski, et al., 1984).

Figure 4 shows the mass burned fraction variations with time for mixture at ϕ=0.7 for various initial pressures. Significant differences in the slope of mass burned fraction curves can be seen which imply a noticeable variation of combustion duration. The combustion with lower initial pressure is faster than that with higher one.

The flame initiation period and combustion duration variations for mixtures of ϕ=1.0 and 0.7 are presented in Fig. 5 as a function of initial pressure. For mixture of ϕ=0.7, it can be obviously seen that the flame initiation period and combustion duration are increased with an increase in the initial pressure of the mixture which in turn indicates that the flame propagation speed is lower for higher initial pressures as

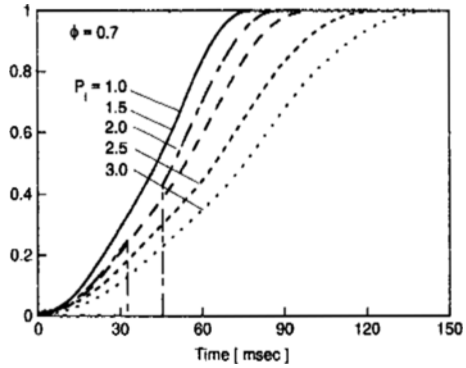

Fig. 4 Mass burned fraction versus time for various initial pressures.

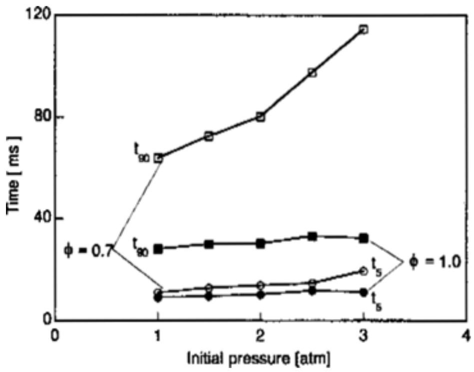

Fig. 5 Variations of flame initiation period and combustion time with initial pressure.

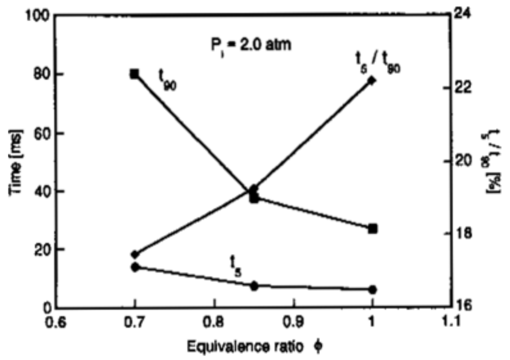

Fig. 6 Flame initiation period, combustion time and their ratio versus equivalence ratio.

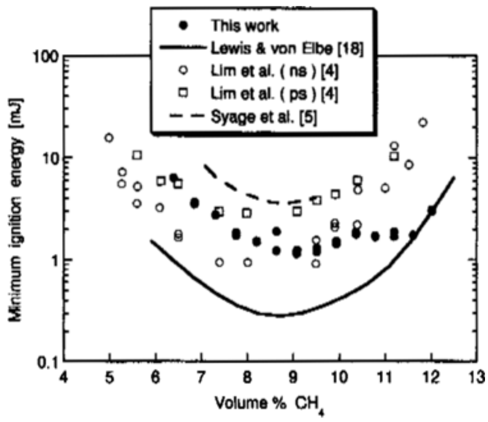

Fig. 7 Measured and calculated minimum ignition energies for CH_4-air mixtures at $P_i=1.0$ atm.

mentioned earlier. The flame initiation period and combustion duration for mixtures of $\phi=1.0$, however, are increased slightly with the initial pressure. The present results are in good agreement with the results obtained using electrical spark plug ignition (Arcoumanis and Bae, 1992).

Figure 6 shows the characteristics times for the flame initiation period, t_5, the combustion time, t_{90}, and the ratio of t_5/t_{90} as a function of the mixture equivalence ratio. The flame initiation period increases significantly for lean mixtures and is well correlated with combustion time. Similar result was obtained using the electrical spark plug ignition with propane-air mixtures (Arcoumanis and Bae, 1992). This behavior can be attributed to the significant cycle-to-cycle variations in lean mixtures, since it has been suggested that the cyclic variations in homogeneous charge spark ignition engine originate during the initial period of combustion from the time of spark breakdown to a noticeable departure of cylinder pressure from the compression pressure (Ko, et al., 1991).

The combustion time for $\phi=0.7$ is about three times as long as that for stoichiometric mixture due to the lower laminar flame speed for lean mixtures. The ratio of flame initiation period to combustion time, t_5/t_{90}, however, decreases as the mixture become leaner contrary to the data obtained with electrical spark plug ignition (Arcoumanis and Bae, 1992). The present results imply that the laser-induced ignition can solve the problem of the cycle-to-cycle variation encountered in the spark ignition engines since it has been suggested that in order to eliminate the cycle-to-cycle variation in lean mixtures, the flame initiation period must be reduced (Arcoumanis and Bae, 1992). Similar trends were obtained for all initial pressures examined. It is to be noted that the all previous results were obtained using nearly the same laser power.

The results of minimum ignition energy (MIE) measurements are demonstrated in Fig. 7 for various CH_4/air mixtures and compared with the previous laser (Lim, et al., 1995) and the electric discharge (Lewis and von Elbe, 1987) measurements and calculations (Syage, et al., 1988). A higher MIE for laser-induced ignition of a given gas mixture than for corresponding electric discharge ignition can be seen. The discrepancy between the two sets of results that decreases toward the flammability limits (upper flammability limit for this work and lower flammability limit for the work of Lim et al., (1995)) can be attributed to the dependence of ignition energy on the spark kernel size. A critical energy deposition size d_{opt}, which minimizes the MIE was found (Ronny, 1994).

For an energy deposition diameter $d>d_{opt}$, the MIE increases slowly with d because a larger volume of mixture than required should be heated. The MIE, however, increases more rapidly for $d<d_{opt}$ because the energy is being deposited in a smaller volume which results in higher

peak temperatures and temperature gradients, thus there will be greater radiative loss from the gas. This in turn results in a larger portion of the deposited energy being dissipated in ways that are not useful for ignition. The closer agreement between the electric and laser spark experiments for significantly lean or rich mixtures would suggest that ignition volume for these mixtures was sufficiently small but for near stoichiometric mixtures was too large (Lim et al., 1995).

Another contribution to the high energy for the laser spark ignition may be the energy loss via the shock wave resulted from the initial expansion of flame kernel (Lim et al., 1995). This shock wave can disperse energy to the surrounding, reducing the energy density within the kernel.

As shown in Fig. 7 differences between the present work and the work by Lim et al. (1995) are also observed. These may be due to the differences in the optical systems used such as the focal length of lens (100 mm for this work and 50 mm for Lim et al. (1995)) and laser beam diameter (7 mm for this work while Lim et al. (1995) did not reported this information). It is well known that the minimum power density required for breakdown depends on the size of focal spot (Hickling and Smith, 1974) which in turn depends on the laser beam diameter and the wavelength and the focal length of lens according to the following:

$$I = W/A$$

where

$$W = E/\tau$$
$$A = \pi d^2/4$$
$$d = 4\lambda f/\pi d_i$$

and I is the laser power density (W/cm²), W is the laser power in a pulse (W), E is the laser pulse energy (J), τ is the laser pulse duration (s), A is the area of the laser focus (cm²), d is the diameter of the laser focus (cm), l is the laser wavelength (cm), f is the lens focal length (cm), and d_i is the laser beam diameter (cm).

Figures 8 and 9 show the combustion pressure profiles and the flame initiation period and the combustion time for mixture at $\phi = 0.7$ and the atmospheric initial pressure as a function of the

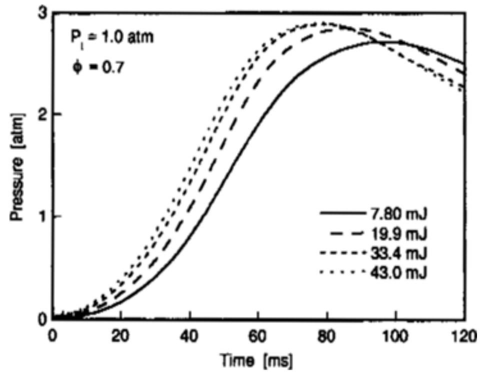

Fig. 8 Combustion pressure rise as a function of time for various energy absorbed by spark.

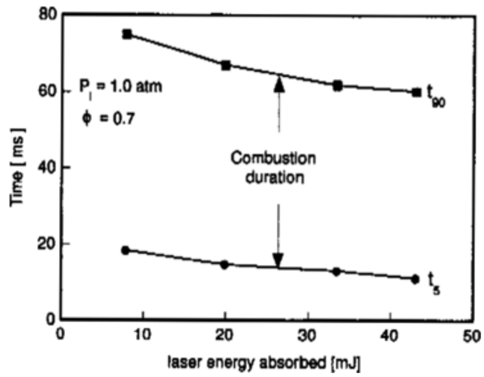

Fig. 9 Combustion duration and flame initiation period as a function of laser energy absorbed by spark.

energy absorbed by spark, respectively. Increasing the spark energy up to 33.4 mJ increases the maximum combustion pressure, decreases both flame initiation period and combustion time significantly. It has been reported before that the higher ignition energy caused both larger and more rapidly growing initial flame kernels which could be attributed to the flame kernel expansion to accommodate the energy deposited by the ignition spark (Ho and Santavicca, 1987).

The maximum combustion pressure, flame initiation period and combustion time appeared to be less sensitive to spark energies above ~33.4 mJ. The decreased sensitivity may be related to the formation of a shock wave generated by the spark (Medoff and McIlroy, 1996). Since the energy deposition in case of laser induced spark occurs in <10 ns, the spark is initially at high temperature and pressure. The resulting relaxation of the over-pressure by expansion of the spark kernel causes a shock wave to emanate from the region of the spark kernel. The energy carried away from the spark kernel by the shock wave is likely to have a non-linear dependence on the spark energy. Thus, at higher spark energies more energy would be lost to the shock wave and thus less energy would be available to drive the kernel expansion.

4. Conclusions

The combustion characteristics and minimum ignition energies in the laser-induced spark ignition were demonstrated for quiescent methane-air mixtures using a shadowgraphy and pressure measurements. The parameters examined included initial pressure and equivalence ratio as well as spark energy. The main findings of this investigation can be summarized as follows:

(1) Ignition kernel exhibits nearly separated two kernels, one of which grows back towards the origin of ignition laser. Eventually after a short time, the two flame kernels separate into two flame fronts propagate individually which is unique in the laser-induced ignition.

(2) For a given mixture, lower initial mixture pressure and higher spark energy resulted in shorter flame initiation period and faster flame propagation.

(3) The ratio of the flame initiation period to combustion time, t_5/t_{90}, decreases as the mixture become leaner contrary to the data obtained with the electrical spark plug ignition.

(4) The laser ignition results lie at higher energy than the electric discharge results, however, the difference decreases toward the lean and rich flammability limits.

Acknowledgment

This work was supported by Hyundai Motors Company.

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