LASER INDUCED SPARK IGNITION AND THE EFFECT OF LASER ENERGIES ON LAMINAR FLAME DEVELOPMENT OF ISO-OC TANE – AIR AT EARLY STAGES

I Made Suardiāja

Department of Mechanical Engineering, Gadjah Mada University
Email: madensuar@ugm.ac.id

ABSTRACT

Laser ignition experiments to investigate the effect of laser energies on laminar flame development was conducted in a fixed stirred vessel. Iso-octane-air mixtures at equivalence ratios ($\phi$) of 0.8 and 1.0, with an initial temperature of 358 K and pressure of 1 bar were ignited by a focused laser beam. Laser energies of 140 mJ and 50 mJ were used to ignite the mixtures. The results show that the flame kernel development increased rapidly as the laser energy increased. The effect of increasing laser energy for a mixture of $\phi = 0.8$ was more dominant than that of $\phi = 1.0$. The higher initial flame speed at higher laser energy was also observed. However, as the flame grew it decreased to a constant value independent of laser energy employed.

Keywords: laser ignition, laminar, vessel, kernel, flame.

INTRODUCTION

The continuing trend towards aircraft of higher speed have led to higher gas velocity and turbulence within the primary zone of combustion chamber. This can produce a gradual deterioration in the environmental conditions of the conventional ignition unit and ignition plug. This condition requires an ignition system with higher performance, life, and reliability. High energy electric spark ignition has proved reliable to be used as ignition system of aircraft engines (Wilson, 1995). However, relighting at high altitude where the pressure is very low with high velocity of gas in the combustion chamber, fail to give adequate ignition. In order the successful relight can be achieved the aircraft have to be descended.

Laser induced spark ignition has proved to ignite lean mixture at a much smaller amount of energy than that of conventional high energy electric spark ignition. This is very beneficial in reducing NOx to meet the legislation. In addition, the ignition point of laser induced spark ignition can be positioned in the region of the combustion chamber where gas mixture is adequate for ignition without interfere the flow field. Laser ignition also offers more repeatable spark and could be developed to generate multiple site ignition. The laser may significantly reduce the combustion duration which can lead to enhance the engine performance. As the availability of small size high energy pulse laser this novel ignition system is one of the future ignition system. For this reason fundamental study of laser ignition was carried out in order to understand the performance of laser ignition and its effect on flame development.

Basically, physical mechanism of laser ignition can be classified into three types, depends on the mode of energy deposition. The relative importance of each mechanism depends on the wavelength of the laser adopted. Firstly, laser thermal heating which is based on rapidly heating of the mixture to its autoignition temperature. However, matching between the laser wavelength and the target molecule's absorption wavelength is needed in order that reaction can strongly absorb the eissis.
sion of the laser beam. Heating of the target reactant was mostly employed with an infra red laser e.g. CO₂ laser (Tanoff et al., 1993; Lee et al., 1996). Secondary ignition may result from the mechanism of resonant multiphoton photochemical. In this case, laser photons dissociate the target molecules into atoms through photodissociation process. The subsequent process is a resonant multiphoton photoionization of an atom which produces free electrons. These electrons become the seed materials for the creation of a laser produced spark (microplasma). This type of ignition method requires a close match between the laser excitation wavelength and some resonance wavelength of the fuel or oxidizer in order for dissociation to occur. Forch and Miielrod (1886) found that a tunable laser which operated near 253.6 nm induced photodissociation of oxidizer component, O₂ or NO₂, to produce an O atom. The third mechanism is laser induced spark (LIS) ignition. Laser beam is focused into the combustible mixture at a selected position in the combustion chamber. The electrical field strength of the focused laser beam is sufficient to cause breakdown of the gas mixture and create a plasma kernel or spark, leading to ignition. The laser beam required to initiate the spark is typically pulse or Q switch laser with pulse duration of nanoseconds or picoseconds. CO₂ laser and Nd:YAG lasers at near infrared and visible spectrum have been used to ignite hydrocarbon - air mixture (Dale et al., 1978, Hanson et al., 1988, Spigelman et al., 1995, Ma et al. 1997). In comparison with the other ignition methods, laser induced spark ignition is less selective about its laser wavelength. In fact, the most important thing is the laser power density at the focus, which must be sufficiently high to generate heat for ignition. Consequently, this ignition method is reliable for the application in aircraft gas turbine engine, since powerful small sized infrared diode laser are now widely available. In this present work LIS ignition method was employed. This present paper reports the preliminary experiments work in using laser ignition to ignite iso-octane air mixtures. The effects of laser energy or laminar flame development at least and stoichiometric conditions are considered. Schlieren technique with a high speed camera was used to diagnostic the flame development.

**EXPERIMENTAL APPARATUS AND TECHNIQUE**

The experiments were conducted in a fans stirred vessel. It comprised a cast stainless steel spherical vessel of 380 mm with extensive optical access via 3 pairs of orthogonal windows of 150 mm diameter and 100 mm thickness. It was capable of withstanding explosions generated with fuel - air mixtures of initial pressure and temperature up to 1.5MPa and 600 K. The vessel was equipped with four fans driven by electric motors. The fans could be used to generate turbulence within the vessel. In laminar flame experiments fans are only run at initial stages to ensure a uniform mixture is achieved.

The mixture preparation was done after evacuation of the vessel. The required amount of iso-octane was first injected into the vessel using a glass syringe through, a rubber bung set into the end wall of the vessel. Then the vessel was filled with cylinder air (supplied by BOC) to 1 bar pressure. The initial temperature of the mixture was set at 355 K, to ensure complete evaporation of the fuel. To reach this temperature the bomb was first heated to a temperature higher than 358 K using its internal 2 kW electric heater, while the fans were running. Prior to ignition the fans were turned off to ensure laminar conditions was attained.

The laser ignition system comprised a laser, beam steering optics, laser energy adjustment system and a Spectra power meter. General arrangement of the laser ignition system is shown in Figure 1. The energy source for the laser ignition system was a Q switched pulsed Nd:YAG laser with pulse duration of 15 ns. The laser beam of 1009 nm wavelength was utilised with a pulse repetition rate of 10 Hz and beam diameter of 6 mm. The maximum energy of the laser beam was 600 mJ per pulse but only 140 mJ and 50 mJ were used to ignite the mixtures.

The output laser beam from the laser head was directed through a 45 degree high energy mirror to the beam steering optics. The latter consisted of two Glan laser high energy polarisers of 15 mm diameter, a half wave plate of 25.4 mm diameter, a Spectra power meter, a beam expander (enlarges the beam 6 times) and a focusing lens of 450 mm focal length. The beam energy was measured using an OPHIR power meter.

The method used to visualise the flame was high speed schlieren photography. The optical ar-
Experimental Results and Discussion

Shown in Figure 2 are the schlieren images of iso-octane - air flame at equivalence ratio of 1.0 for laser energies of 50 mJ and 140 mJ. The laser beam incident on the top of the pictures. It clearly shows that the size of flame kernel increases as laser energy increases. The propagation of flame front towards the incoming laser beam is much faster than that in horizontal direction. The former is a typical characteristic of flame kernel generated by LIS ignition, which result in an elongated kernel, known as a third lobe. The mechanism of its formation has not been known very well, however, some theories has been proposed for its mechanism (Hasen et al., 1988, Spiglanin et al., 1996). The flow field produced by laser induced gas dynamic and laser thermal heating are thought to affect its formation. At higher laser energy the...
effects of flow field and thermal heating are stronger than that at lower one. As a result, a longer third lobe is observed when the laser energy is higher.

Since the propagation of flame front towards the incoming laser beam is faster than that in horizontal direction, the ratio of magnitude of these propagations is considered. The temporal variation of this parameter at different laser energies and equivalence ratios is presented in Figure 3. The values of this parameter increase as laser energy increases. They also increase when equivalence ratio is increased from \(? = 0.8\) to \(? = 1.0\), for the both laser energy. At high laser energy of 140 mJ and below 0.5 ms this parameter increases rapidly from low value (\(< 0.8\)) to values of 1.1 and 1.5 for \(? = 0.8\) and \(? = 1.0\), respectively. After about 1 ms its values are almost constant. At low laser energy of
50 mJ this parameter increase gradually when $\phi = 1.0$ and approximately constant of about 1.0 after about 3 ms. However, when $\phi = 0.8$, it initially decreases from 0.4 to 0.25 up to 1.2 ms, and then it increases gradually. The higher values of this ratio at $\phi = 1.0$ suggesting the dominant effect of flow field in assisting the propagation of flame front in vertical direction. In other hand, the propagation in horizontal direction is assisted by plasma expansion, which is almost similar for different equivalence ratio at the same laser energy. As low laser energy the propagation in vertical direction is very slow due to the weak effect of flow field. This propagation is slower than that in horizontal direction which result in the values of the parameter is lower than one.

Shown in Figure 4 is the temporal variation of mean flame radius at different energies and equivalence ratio. The effect of laser energy is obvious that flame radius increases as laser energy increases. At laser energy of 140 mJ the main flame radius of $\phi = 1.0$ is similar to that of $\phi = 0.8$ up to about 2 ms after ignition. This might be due to the effect laser energy in "overdrive" the initial kernel at this period. After that the higher growing of flame kernel at $\phi = 1.0$ is obtained. For low laser energy of 50 mJ, the main flame radius is much higher when $\phi = 1.0$ compared to that of $\phi = 0.8$. The increase of flame radius for $\phi = 1.0$ is less than two fold when the laser energy was increased from 50 mJ to 140 mJ. However, it is more than two fold for $\phi = 0.8$. This suggest that increasing laser energy from 50 mJ to 140 mJ enhance burning rate, thus, reduce combustion duration at lean mixtures. This is beneficial especially in lean burn engine strategy.

![Image of Figure 4](image)

Flame speed against radius at early stages of combustion is presented in Figure 5. Below flame radius of 12 mm the flame speed drop from very high values to a minimum. The minimum is given by a decaying support from the spark plasma and flow field and the increasing effect of stretch and burning velocity. The spark energy is important in "overdrive" the flame kernel to avoid it from quenching due to the increasing effect of stretch (Bradley et al. 1996). As the flame grow the stretch effect decreases and the flame development is then influenced by chemical reaction. After radius of 12 mm the flame speed at $\phi = 1.0$ is higher than that at $\phi = 0.8$, suggesting that chemical reaction has dominated the effect of flame kernel propagation. As the flame grows to radius of higher than 15 mm, the flame speed of high energy is approaching to that low low energy.
CONCLUSIONS

1. Laser induced spark ignition offers the possibility to site the ignition point at a favourable position in the combustion chamber without interfering the flow field.

2. The flame development increases rapidly as laser energy increases. A more dominant effect of increasing laser energies was observed for the mixtures of equivalence ratio of 0.8 than that of 1.0.

3. A higher initial flame speed was obtained for laser energy of 140 mJ than that of 50 mJ. However, the speeds approach the same value for the mixtures of the same equivalence ratio as the mean flame radius higher than about 13 mm.

REFERENCES


of H/0/Ar mixtures, Combustion and Flame 102, 310 - 328.
