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Analysis of Combustion and Flame Propagation Characteristics of LPG and Gasoline Fuels by Laser Deflection Method

Ki Hyung Lee*, Chang Sik Lee
Department of Mechanical Engineering, Hanyang University, Kyunggi-do 425-791, Korea
Jea Duk Ryu
Graduate school of Hanyang University, Kyunggi-do 425-791, Korea
Gyung-Min Choi
Department of Mechanical Engineering, Osaka University, 2-1 Yamadaoka, Suta, Osaka, 565-0871, Japan

This work is to investigate the combustion characteristics and flame propagation of the LPG (liquified petroleum gas) and gasoline fuel. In order to characterize the combustion processes of the fuels, the flame propagation and combustion characteristics were investigated by using a constant volume combustion chamber. The flame propagation of both LPG and gasoline fuels was investigated by the laser deflection method and the high-speed Schlieren photography. The result of laser deflection method show that the error of measured flame propagation speed by laser method is less than 5% compared with the result of high-speed camera. The flame propagation speed of the fuel is increased with the decrease of initial pressure and the increase of initial temperature in the constant volume chamber. The results also show that the equivalence ratio has a great effect on the flame speed, combustion pressure and the combustion duration of the fuel-air mixture.

Key Words : Constant Volume Combustion Chamber, Laser Deflection Method, High Speed Camera Method, Flame Propagation Speed, Combustion Duration, Equivalence Ratio

1. Introduction

In recent years, the environmental issue due to the automotive emissions has been one of the most important concerns all over the world. In the point of the reduction of exhaust emission, liquefied petroleum gas (LPG) is a useful alternative fuel because of sufficient supply infrastructure and higher heating value. LPG fuel also has merits in the operating characteristics under the high compression ratio because it has higher octane value and lower exhaust HC emission compared with the combustion of gasoline. In order to improve the engine performance and exhaust emission of automotive engine, it is necessary to optimize the fuel supply system and combustion chamber geometry. In order to improve the combustion performance of LPG engine, the identification of combustion characteristics for gas fuel in the engine is important to obtain the stable combustion of the gas fuel. Especially, the measurement of flame propagation and combustion phenomenon is necessary to analyze the combustion of gas fuel in the chamber.

The combustion analysis of LPG fuel in the constant volume combustion chamber have been

* Corresponding Author,
E-mail : hylee@hanyang.ac.kr
TEL : +82-31-400-5251; **FAX** : +82-31-406-5550
Department of Mechanical Engineering, Hanyang University, Kyunggi-do 425-791, Korea. (Manuscript **Received** November 15, 2000; **Revised** May 21, 2002)

the subject of theoretical and experimental study for many years. Combustion characteristics of LPG fuel in the chamber can be enhanced by increasing the ambient temperature and the air flow in the region of combustion. Flame propagation and flame development process have been measured by Arcoumanis and Bae (1992), Ting et al. (1994) and many researcher (Lim et al., 1992 ; Cheong et al., 1995 ; Bae 1996). Numerous studies on the flame speed and propagation processes of LPG fuel have been carried out, however, most of these research have investigated only the combustion process by using the high-speed camera. The high-speed photographs of combustion process have many problems such as image processing due to the development of film and expensive cost for the photographs of combustion processes.

The objective of this paper is to investigate the combustion characteristics and flame propagation speeds of the LPG and gasoline in a constant volume combustion chamber.

In order to obtain the effective method for the determination of flame propagation speed, the characteristics of flame propagation speed of LPG and gasoline fuel at various initial conditions were investigated by using the laser deflection method and high-speed camera method. In addition, the speed of flame propagation of LPG fuel is compared with that of gasoline in the constant volume chamber. The combustion characteristics and flame propagation of two fuels in the chamber were also investigated at various chamber condition by laser deflection and high-speed camera system.

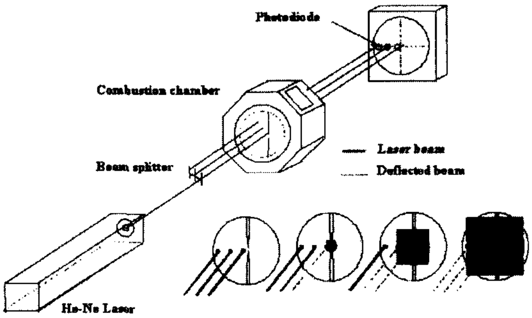
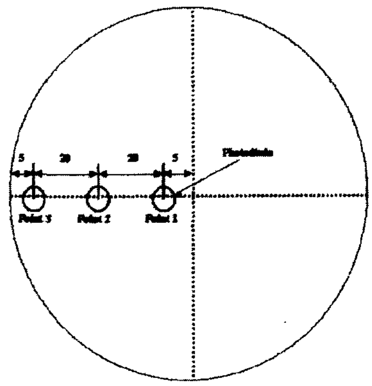
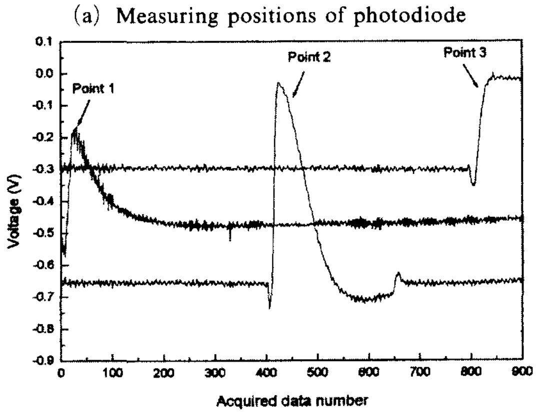


Fig. 1 Detection system of flame propagation speed



(a) Measuring positions of photodiode



(b) Signal of photodiode

Fig. 2 Positions and signal of Photodiode

2. Experimental Apparatus and Procedures

2.1 Optical system of a laser deflection method

Laser deflection method has been applied to measure the speed of flame propagation between two beams by recording the time when a flame front passes each laser beam (Arcoumanis and Bae, 1992 ; Ting et al., 1994 ; Cheong et al., 1995).

Figure 1 shows the optical system used for the investigation of the flame propagation in the constant volume chamber. It consists of a He-Ne laser, beam splitter and photodiodes. The beam splitter, which is composed of a full reflection mirror and two half-reflection mirrors, divides the laser beam into three beams. Each beam horizontally passes through an optical window installed at the combustion chamber and is accurately focussed on the control volume by a beam translator. The beam passes through three measuring points which are located at 5mm, 25mm and 45mm from the center of spark gap in a radial direction.

Figure 2 shows the positions of the photodiode and an example of signals detected by a photodiodes.

Fuel supply system is composed of the fuel

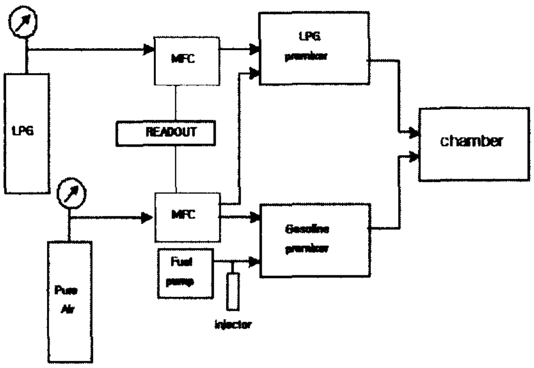


Fig. 3 Schematic diagram of fuel supply system

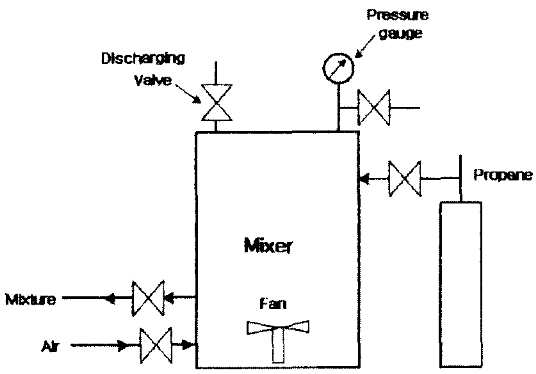


Fig. 4 Configuration of LPG premixer

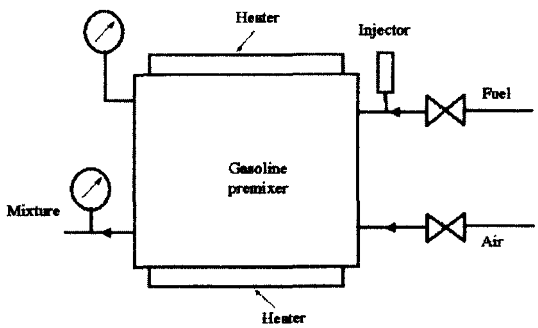


Fig. 5 Gasoline premixer

storage bomb, LPG controller, premixing chamber and the constant volume chamber as shown in Fig. 3. The used fuels were gasoline and propane which is a main component of the LPG fuel. The physical properties of the test fuels are ρ=720kg/m^3 for gasoline and ρ_g=2.0082kg/m^3 for LPG which corresponds to 100% pure propane.

A mass flow controllers (MFC) were used to control the equivalence ratio precisely in this experiment. In order to obtain the mixing of the fuel and air, premixers consisted of the air, fuel control valves and the heating chamber as shown in Figs. 4 and 5. A fan was equipped on the lower part in the LPG premixer. The heating system with two heating plates of 0.4 and 0.6kW was controlled for the promotive effect of the evaporation and homogeneity of the fuel in the chamber.

2.2 Visualization system for the flame propagation

For the purpose of validating a flame propagation speed measured by the laser deflection method, the Schlieren system was applied for the visualization of the flame propagation. In this experiment, a high speed camera with a rotating prism was used for the measurement of flame propagation speed. The camera speed was set to 3,000 fps (frames per second) and synchronized with the ignition system considering the delay time. In the image capturing process, the light source with 300mW Xenon lamp was

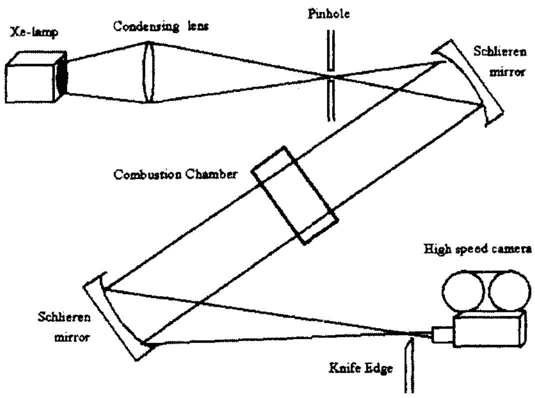


Fig. 6 Schematic diagram of the visualization system

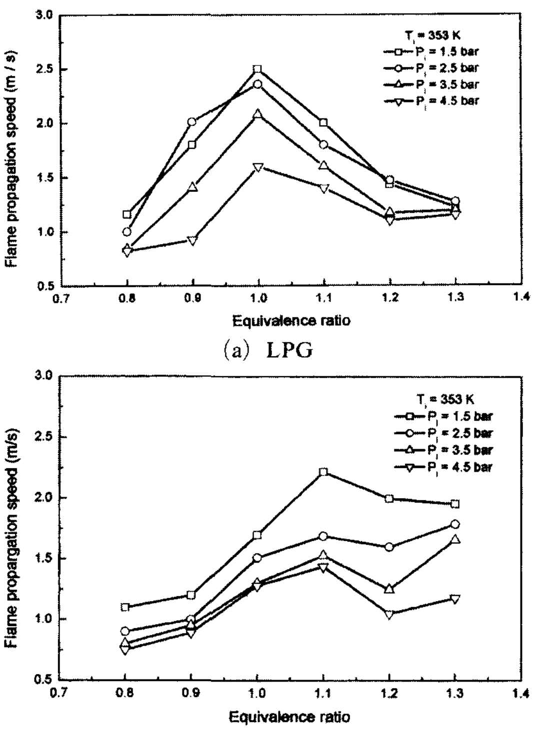
focussed on the combustion chamber located between two concave mirrors of 300mm effective diameter.

Experiments were performed for two fuels of LPG and gasoline at various pressure conditions in the combustion chamber with constant temperature 353K. High-speed photographs were taken for flame propagation and combustion process at each fuel and experimental conditions using the optical arrangement and the experimental apparatus as shown in Figs. 1 and 6.

3. Experimental Result and Discussion

3.1 Comparison of flame propagation characteristics between gasoline and LPG fuel

Figure 7 shows the result of flame speed measurements for the LPG and gasoline in the constant volume chamber by the laser deflection system as shown in Fig. 1.



(a) LPG

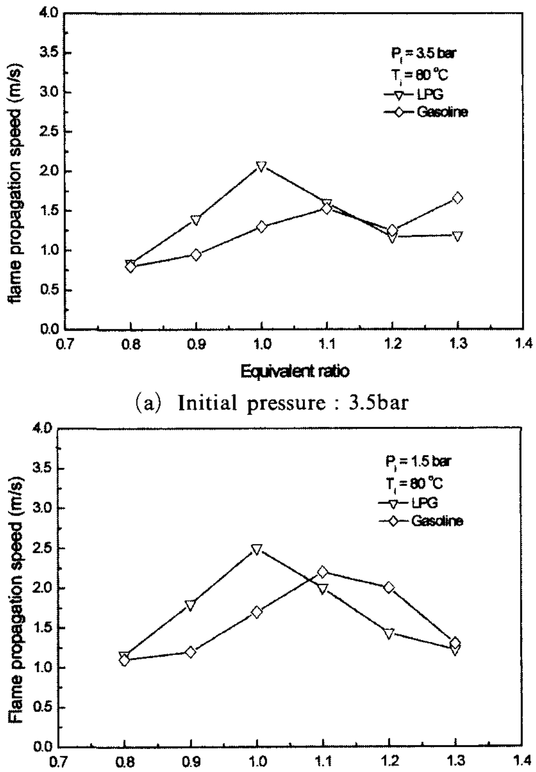
(b) Gasoline

Fig. 7 Characteristics of flame propagation speed at T_I=353K

Based on the experimental results, it was found that the flame propagation speed in the combustion chamber has a remarkable variation with the change of equivalence ratio at different initial chamber pressures. Both LPG and gasoline fuel showed maximum flame propagation speeds near the stoichiometric fuel-air ratio that is an equivalence ratio, $\Phi=1.0$ (for gasoline, it occurs in a little richer zone of $\Phi=1.1$). In the case of LPG fuel, the flame propagation speed decreases in the rich mixture zone, however, in the case of gasoline, the decrease of flame propagation speed is not so large, and on the contrary the propagation speed in some regions increases.

Figure 8 shows the comparison of the flame propagation speeds for gasoline and LPG fuel at two different pressures in the chamber.

The flame propagation speed of the LPG was higher in the lean mixture region, but that of



(a) Initial pressure : 3.5bar

(b) Initial pressure : 1.5bar

Fig. 8 Comparison of flame propagation speed between gasoline and LPG fuel at T_I=353K

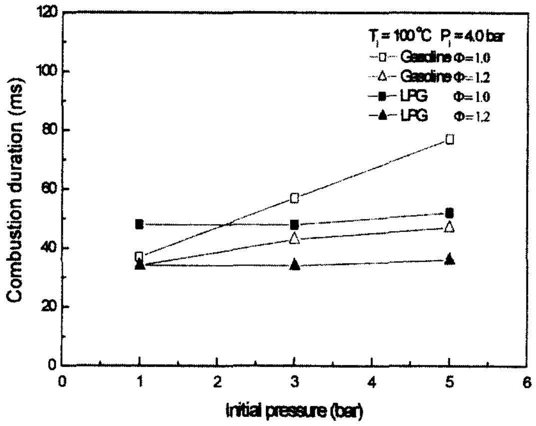


Fig. 9 Effect of initial pressure on combustion duration at T_i=373K, P_i=4.0bar

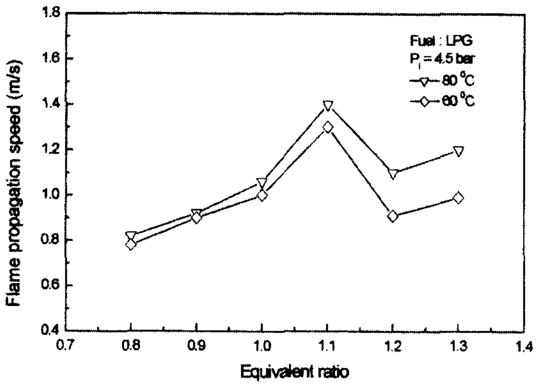


Fig. 10 Flame propagation speed for two different initial temperature as a function equivalence ratio at P_i=4.5bar

gasoline was promoted in the rich mixture region. This trend was the same at two pressure conditions of the chamber, so that LPG fuel has the better characteristic as a fuel of the lean burn engine.

Comparing the photographs of flame development, the flame propagation speed of the LPG is faster than that of gasoline at the stoichiometric fuel-air ratio. In the point of the optimum theoretical ratio for the engine, the compression ratio of the LPG engine is higher than that of gasoline engine because the LPG is superior to the gasoline in the antiknocking property.

Figure 9 shows the effect of equivalence ratio on the combustion duration of two fuels. As the equivalence ratio increases, the combustion duration is decreased because of the improvement of combustion characteristics in the chamber.

3.2 Analysis of flame propagation process according to initial conditions

Figure 10 shows the comparison of flame propagation speed according to the equivalence ratio for LPG between two different initial temperatures in the chamber. As indicated in Fig. 10, the speed of flame propagation at 80℃ of mixture temperature is higher than that of 60℃ of mixture temperature in all equivalence ratio. The difference of flame propagation speed between two temperatures is increased with the increase of equivalence ratio.

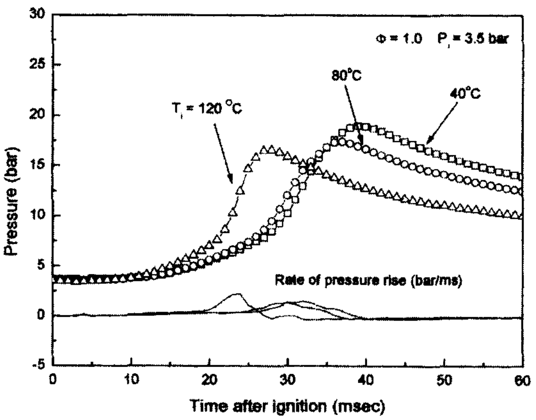


Fig. 11 Effect of different initial temperatures at P_i=3.5bar, Φ=1.0

Figure 11 shows the effect of initial mixture temperature on the combustion pressure. The increase of initial temperature indicates that the time that reaches the maximum pressure is advanced because of improvement of combustion characteristics.

3.3 Analysis of combustion and flame propagation characteristics with equivalence ratio

Figure 12 shows the effects of equivalence ratio on the combustion pressure at the initial temperature of 80℃. The maximum pressure appeared on the equivalence ratio Φ=1.0.

It was found that the combustion pressure has higher value at the stoichiometric fuel-air ratio

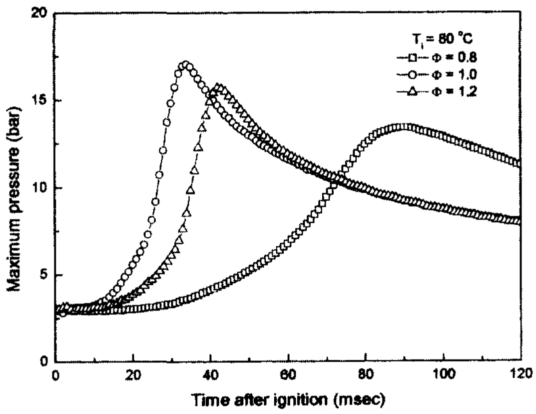


Fig. 12 Maximum combustion pressure versus ignition timing for different equivalent ratios at T_i=353K

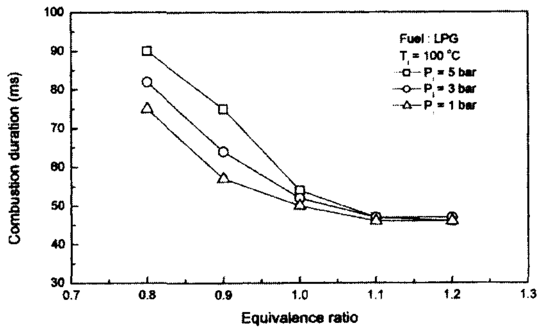


Fig. 13 Combustion duration versus equivalence ratio for different initial pressure at T_i=373K

with the optimal combustion condition which is more advanced than the other equivalence ratio. Figure 13 shows that the combustion durations decreased until the equivalence ratio reached Φ= 1.1. It can be seen that the combustion duration is decreased in accordance with the increase of equivalence ratio.

3.4 Visualization of flame propagation of gasoline and LPG

For the purposes of comparing the flame propagation speed measured by high speed camera with the one measured by the laser deflection method, the combustion processes were visualized using a high-speed Schlieren system while measured with laser deflection system as indicated in Fig. 6. All pictures were modified by image processing, so that the flame propagation speed was calculated from these pictures.

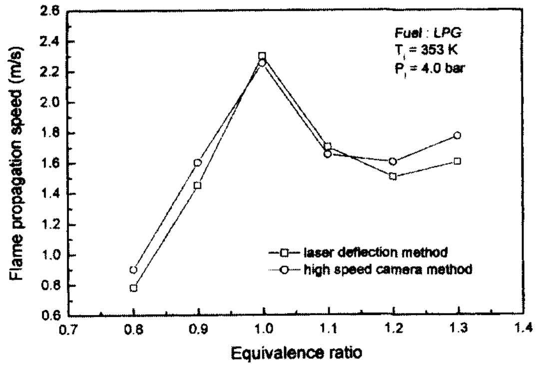
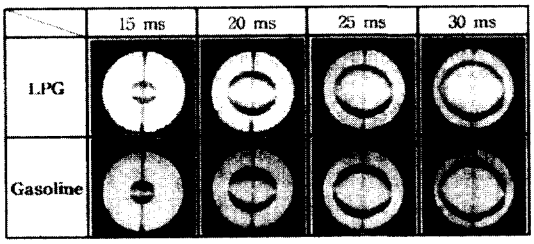
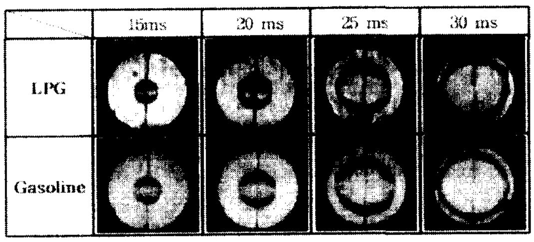


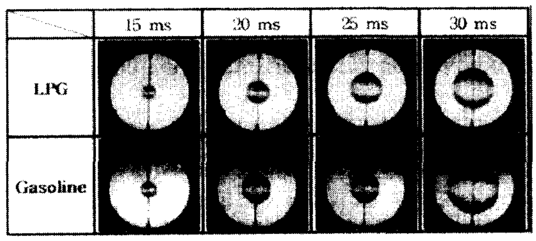
Fig. 14 Comparison of laser deflection method and high speed camera method at T_i=353K, P_i= 4.0bar



(a) Φ=0.8, P_i=4bar, T_i=353K



(b) Φ=1.1, P_i=4bar, T_i=353K



(c) Φ=1.3, P_i=4bar, T_i=353K

Fig. 15 Flame propagation process with equivalence ratio using Schlieren photographs

Figure 14 shows that the error of flame propagation velocity between the laser deflection system and high speed camera system is kept within 5%. From this result, it is found that the laser deflection method which was set up as Fig. 1 could measure laminar flame propagation velocity without such an expensive cost as the case of high speed camera.

Figure 15 shows the comparison of flame propagation between LPG and gasoline at the conditions of 4 bar and 353K. The high-speed photographs were taken for the estimation of the flame propagation speed at each experimental condition using the high-speed Schlieren system.

The difference of flame propagation between two fuels can be obeserved by comparing two visualization results. When the mixture is leaner ($\Phi=0.8$), the flame propagation of LPG is faster than the one of gasoline as shown in Fig. 15 (a). On the other hand, when the mixture is a little richer than stoichiometric equivalence ratio ($\Phi=1.1$), the flame propagation speed is very fast and the flame speed of gasoline is faster than that of LPG. Furthermore, when the mixture is too rich ($\Phi=1.3$), the flame propagation speed is slower than other equivalence ratio and the flame speed of gasoline is also faster than that of LPG.

4. Conclusions

An experimental study of the measurement of flame propagation speed by using a high-speed Schlieren system and a laser deflection system has been performed.

The influence of the initial conditions in the chamber on the flame propagation speed and combustion characteristics was investigated.

Considering the results of this investigation, the following conclusions were obtained.

(1) A technique for the measurement of flame propagation speed using the laser deflection method was developed. As a result, the flame propagation speed of the fuel-air mixture was measured by the laser deflection method and had a good reliability with the maximum error lower than 5%.

(2) As the ambient pressure decreases, the flame propagation speeds increase for both LPG and gasoline. The maximum flame propagation speed appeared at the stoichiometric equivalence ratio condition ($\Phi=1.0$) for LPG, but at equivalence ratio of 1.1 for gasoline, respectively.

(3) The comparison of the flame propagation between LPG and gasoline showed that the flame speed of LPG is faster than that of gasoline at the range of lean or stoichiometric equivalence ratios. However at the range of rich equivalence ratio conditions, the speed of flame propagation for the gasoline was superior to that of LPG.

(4) For LPG, as the initial temperature increased, the flame propagation was faster than the gasoline, while the time that the maximum pressure occured was advanced.

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