Comparison between Laser Ignition and Spark-Plug Ignition of Flowing Propane-Air Mixtures

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1 Introduction

After passively-Q-switched diode-pumped lasers were developed, the size of the laser head can be as small as a conventional automobile spark plug. Therefore, laser ignition is now being studied as a new practical ignition technology to replace the conventional spark-plug ignition [1]. Our group demonstrated the higher ability of laser-ignition in quiescent propane-air mixtures [2]. However, in actual internal combustion engines, the mixture is rarely quiescent when ignited. In the past, some researchers studied the effect of flow on spark-plug ignition [3,4] and laser ignition [5,6] independently. However, no experiment was found in which laser ignition was compared with spark-plug ignition in flowing pre-mixed fuel-air mixtures under comparable conditions. In the present work, we compared the ability of laser ignition with that of spark-plug ignition in flowing pre-mixed propane-air mixtures at different flow speeds and equivalence ratios with the same absorbed energy.

2 Experimental Setup

Figure 1 shows a general view of the experimental setup. The combustor was a straight PMMA (polymethylmethacrylate) circular pipe, whose inner diameter was 20 mm, thickness was 10 mm, and length was 940 mm. A 60-mm-long brass tube was connected at the downstream side of the combustor. A spark plug and optical lenses for laser ignition were installed at 450 mm from the upstream end of the combustor. We used plano-convex lenses with a focal length of 15 mm for focusing and diagnosing the laser light. We measured the incident and transmitted laser energies using two energy monitors and obtained the absorbed energy as their difference. In the experiments, we used Nd:YAG laser [LOTIS TII, LS-2131M], whose wavelength was 1064 nm and effective pulse duration was about 12 ns. Also, we used a spark plug of semi-surface discharge type [NGK-R847-11], which was driven by an ignition coil [TOYOTA, 90919-02240]. The discharge duration of the spark plug was approximately 1.6 ms. The laser was focused on the central axis of the tube, but the spark-plug was installed on the side wall of the tube. In the present experiments, the deposited energy was approximately 25 mJ in both ignition methods.

We created a gas flow in the combustor by using the moving piston driven by a choked air flow from the high-pressure tank as shown in Fig. 1. The moving-piston tube was made of PMMA, whose inner diameter was 101 mm, thickness was 7 mm, and length was 1000 mm. According to Ref. [7], flow in a

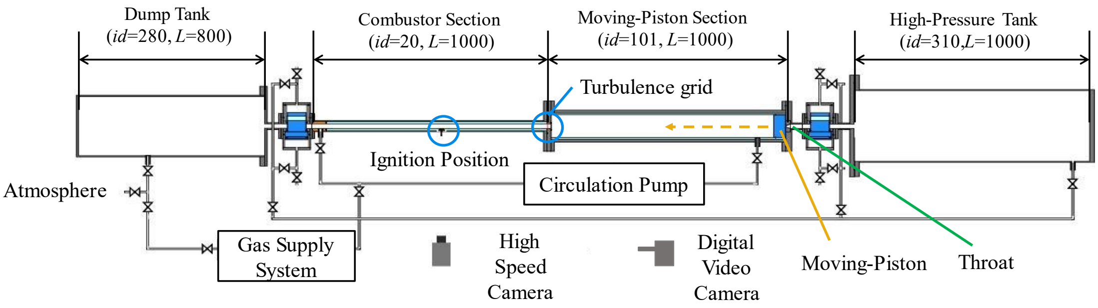

Fig. 1 Experimental setup.

channel is, in general, turbulent when *Re* > 5000, and additionally, the entrance length of approximately 40 times the diameter is required to form a fully developed turbulent flow. In the present experiments, we used a grid to form a developed turbulent flow within a shorter distance. The turbulent flow that the grid induces is expected to be settled down to a degree of 10^{-2} at approximately 150 mm from the grid [8].

We used a high speed camera [PHOTRON, FASTCAM SA4] to observe self-emission in the combustor, with the frame rate of 4000 fps and the exposure time of 1/4000 s. Also, we observed the movement of the moving piston by a digital video camera [SONY, FDR-AX700]. In the experiments, we used pre-mixed propane-air gas mixtures at 100 kPa and approximately 20 degrees Celsius, where the mole fraction of propane was varied from 2.3% to 4.0% (equivalence ratio: 0.56-1.0). The pre-mixed flammable gas mixture was prepared in the combustor using a circulation pump.

3 Results and Discussion

3.1 Ignition ability

Figure 2 summarizes the ignition ability obtained in the experiments. The vertical axis shows the fraction of successfully-ignited events in 10-times repeated experiments for each condition. The horizontal axis shows the mole fraction of propane in the mixtures, where 4.0% corresponds to the stoichiometric ratio. The error in the horizontal axis is approximately $\pm0.1\%$ corresponding to the accuracy of the pressure gauge used in the experiments. The flow speed in the combustor was calculated from the measured moving-piston speed taking account of the ratio of the cross-sectional

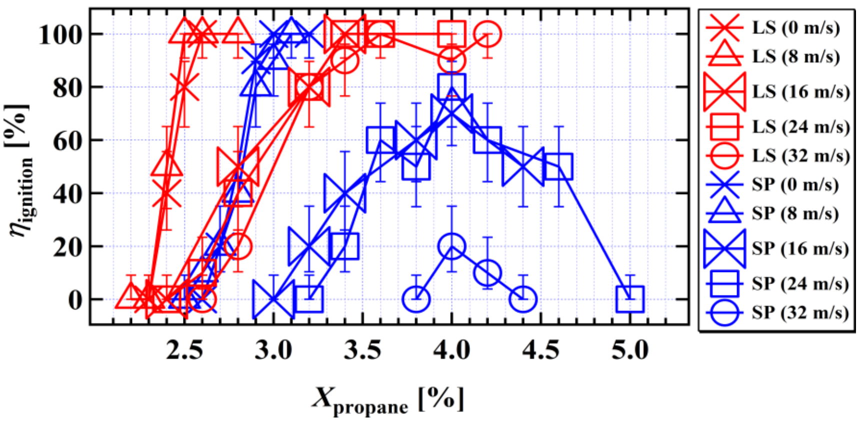

Fig. 2 Ignition success rates. LS and SP denote Laser Spark and Spark Plug, respectively. $X_{propane}$ denotes the mole fraction of propane in the mixtures.

areas of the combustor and the moving-piston tube. The flow speed shown in Fig. 2 is the average speed between the times of -100 ms and $+10$ ms, where the time origin corresponds to the beginning of the spark.

First, we discuss the reason for the observed higher ability of the laser ignition. The pulse duration of the igniting laser was about 10^{-8} s, whereas that of the spark-plug breakdown was about 10^{-3} s. Therefore, when the flow speed is in the range of 10–100 m/s, the flammable gas moves less than 1 μm within the laser-pulse duration, which is negligible compared with the size of the initial flame kernel of a few millimeters, but moves more than 10 mm within the spark-plug breakdown duration, which is larger than the size of the initial flame kernel. Therefore, even if the deposited energy is the same between the laser ignition and the spark-plug ignition, the energy deposited per unit volume is much smaller in the case of the spark-plug ignition due to the flow. Although heat loss to the electrodes and the tube wall and large flow-speed gradient around the initial flame kernel in the case of the spark-plug ignition must contribute to the difference of the ability between the laser ignition and the spark-plug ignition, the difference of five-orders in magnitude in the energy-deposition duration is probably the principal reason for their difference in the ignition ability.

As shown in Fig. 2, the ignition success rates varied sharply between the flow speeds of 8 and 16 m/s in both cases of the laser ignition and the spark-plug ignition. In order to investigate this drastic change of the ignition success rates more, we conducted additional experiments to clarify the detailed variation of the ignition success rates in this flow-speed range at X_{propane} = 2.6% for the laser ignition and at X_{propane} = 3.2% for the spark-plug ignition. As a result, it was found that the measured ignition success rates as functions of the flow speed varied sharply but continuously.

Figure 3 shows the ignition success rates as functions of the flow speed. The results shown in Fig. 3 strongly depend on X_{propane}. In order to understand the ignitable limits, we evaluated the turbulent Damköhler number of first species $Da^{I}{}_{L} = \tau_t/\tau_{ch} = (L/u')/(\delta_{\mathrm{F}}/S_{\mathrm{L}})$, in which δ_{F} is the laminar-flame thickness calculated by $(T_{\mathrm{b}} - T_{\mathrm{u}})/(|\partial T/\partial x|_{\mathrm{max}})$ where T_{u} is the temperature of the unburned gas, T_{b} is the temperature of the burned gas, $|\partial T/\partial x|_{\mathrm{max}}$ is the maximum of the temperature gradient, S_{L} is the laminar burning velocity calculated using the flame speed model of Chemkin-Pro [9] and the reaction model GRI-mech 3.0 [10], u' is the turbulent intensity calculated by $u' = 0.087Re^{-0.079}U$ (for $1 \times 10^4 < Re < 7 \times 10^5$) where Re is the flow Reynolds number and U is the flow speed [11], L is the turbulent integral scale calculated by $L = 0.08d$ where d is the inner diameter of the combustor [12]. We classified the measured ignition success rates into three classes and plotted them in the regime diagram for premixed turbulent combustion as shown in Fig. 4. We cited this diagram from Ref. [13]. When $Da^{I}{}_{L}$ is smaller than unity, it is expected that the flame structure is influenced by the turbulence macroscopically. That is, it is expected that the initial flame karnel cannot grow to

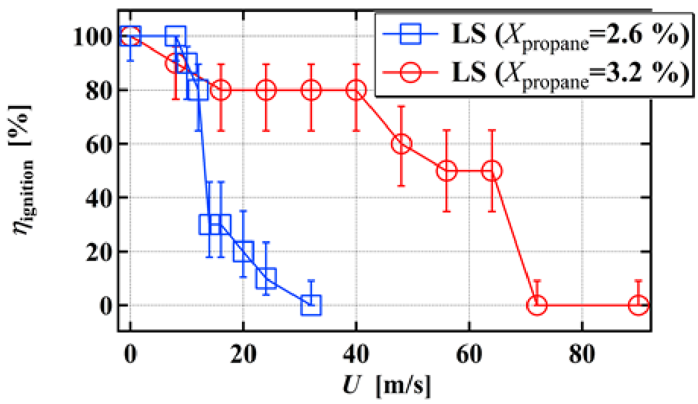

Fig. 3 Ignition success rates as functions of flow speed.

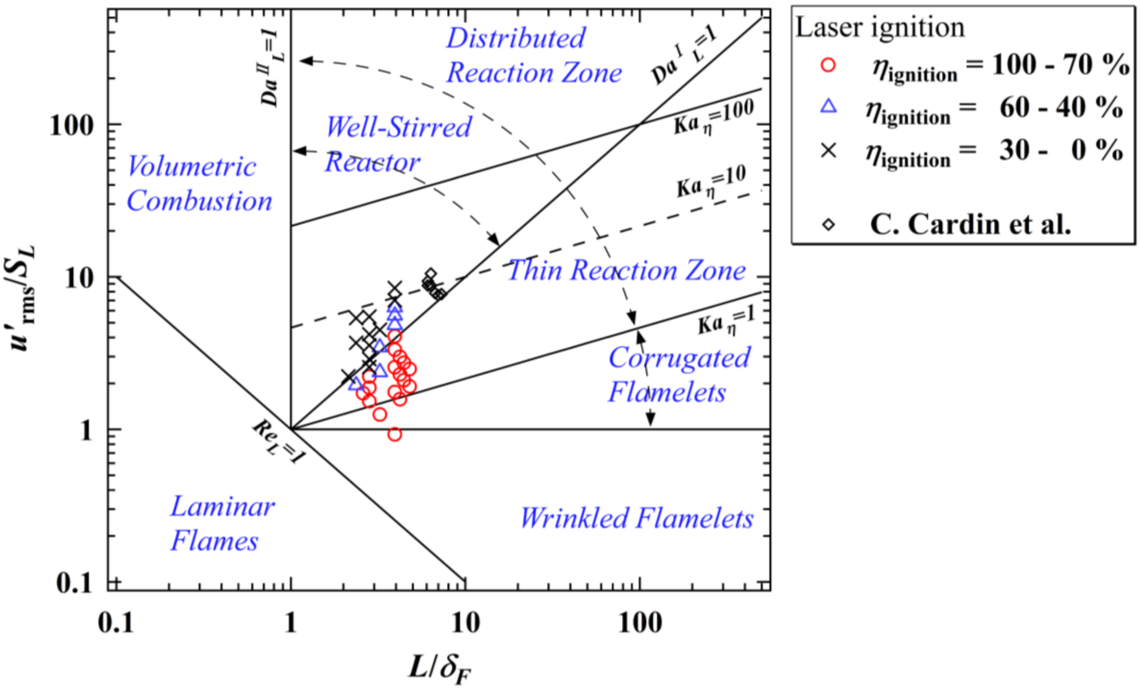

Fig. 4 Ignition success rates on the regime diagram for premixed turbulent combustion.

the propagating flame when $Da^I{}_L$ is smaller than some critical value depending upon the flammable gas species and the ignition conditions.

In Fig. 4, the conditions for the transition phenomenon on the minimum ignition energy (MIE) values experimentally obtained with laser ignition by C. Cardin et al. are also plotted [14]. Although their experiment was quite different from the present experiment, their results are also near $Da^I{}_L \approx 1$. We think that this is not accidental.

3.2 Flame propagation

Figure 5 shows the behavior of the flame propagation, where Δx is the distance between the left and right ends of the self-emission region. As a whole, the flame ignited by the laser began to propagate earlier than that ignited by the spark plug. When the flow speed was 32 m/s, the difference between the two ignition methods seems small. However, it should be noted that the success rate of the spark-plug ignition at this condition was only 20%. That is, the initial flame kernel created by the spark-plug is strongly stretched by the flow-speed gradient near the side wall, and therefore, the survival rate of the initial flame kernel is low although the survived flame kernel develops fast if it is survived.

Additionally, it seems that the propagation speeds of the fully-developed flames are almost the same between the laser ignition and the spark-plug ignition. Figure 6 shows the apparent turbulent burning velocity S_T obtained from the results as functions of the flow speed U, where S_L is the laminar burning velocity. We evaluated S_T as follows. First, the flame speed in the laboratory system (V_F) was evaluated by the formula: $V_F = \mathrm{d}(\Delta x/2)/\mathrm{d}t$. From V_F, we evaluated S_T by the formula: $S_T = (A_C/A_F)(\rho_b/\rho_u)V_F$, where ρ_u and ρ_b denote the mass densities of the unburned and burned gases, respectively, A_C is the cross-sectional area of the combustor, and A_F is the area of the smoothed surface of the flame. As shown in Fig. 6, no significant difference between the two ignition methods was recognized. In addition, the experimental results shown in Fig. 6 seem to agree with the estimations by the empirical formula [15],

$$\frac{S_T}{S_L} = 0.98\left(1+\frac{u'}{S_L}\right) + 0.02\left(1+\frac{\nu_T}{\nu}\right).$$

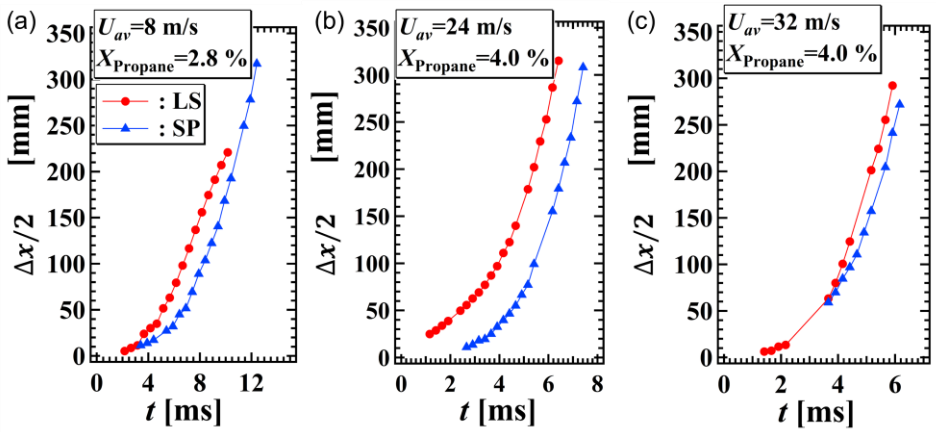

Fig. 5 Flame propagation.

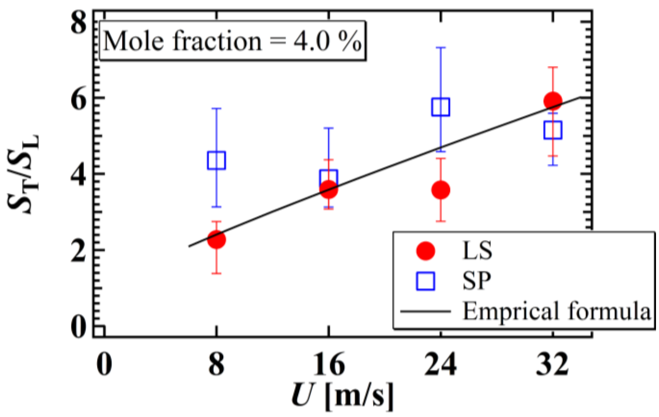

Fig. 6 Apparent turbulent flame velocity.

4 Conclusions

We experimentally compared laser ignition and spark-plug ignition of flowing pre-mixed propane-air mixtures. The conclusions of the present study are summarized as follows.

(1) The ability of the laser ignition was higher than that of the spark-plug ignition.

(2) The flame ignited by the laser began to propagate earlier than that ignited by the spark plug.

(3) The apparent burning velocity of the developed flame was independent of the ignition method.

Acknowledgments

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