Combustion and Flame 178 (2017) 1–6

Contents lists available at ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

# An experimental study on the ignition ability of a laser-induced gaseous breakdown

Takuma Endo*, Yuhei Takenaka, Yoshiyuki Sako, Tomoyuki Johzaki, Shin-ichi Namba, Daisuke Shimokuri

*Department of Mechanical Systems Engineering, Hiroshima University, 1-4-1 Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8527, Japan*

ARTICLE INFO

*Article history:*
Received 7 September 2016
Revised 24 October 2016
Accepted 18 January 2017
Available online 1 February 2017

*Keywords:*
Ignition
Spark
Laser
Electrodes
Propane

ABSTRACT

For examining the ability of laser ignition, a quiescent lean-fuel propane–air mixture was ignited in a constant-volume chamber by a spark induced by a pair of electrodes and an automotive spark driver, a spark induced by focused high-power laser, or a spark induced by focused high-power laser between a pair of dummy electrodes, where the deposited energy into the gas was the same in all cases. In the experiments, the mole fraction of the fuel in the mixture was varied, and the pressure history on the inner wall of the chamber, probability of successful ignition, and the high-speed multi-frame schlieren images of an ignition process were obtained. The results showed that the ignition ability of a laser-induced spark was superior to that of a conventional electrical spark in lean-fuel conditions near the ignitable limit, and that the higher ignition ability of a laser-induced spark was due not only to the lack of heat loss to electrodes but also to a large initial flame kernel whose effective energy was augmented by rapid heat release from the combustible mixture sucked into the kernel by a non-spherical inward flow created by a laser-induced spark. In addition, reinjection of the transmitted laser light into plasma strengthened the ignition ability of the laser. This was predominantly due to the increase of the total absorbed energy.


## 1. Introduction

The development of spark-ignition (SI) engines proceeds toward lean-burn high-compression-ratio engines offering greater fuel economy but requiring durable high-energy ignition devices [1]. In current SI engines, ignition is usually realized by a spark created between a pair of high-voltage electrodes; higher spark energy tends to decrease the life of the spark plug because of increased erosion. Additionally, for lean-burn engines, some technology to facilitate combustion is required so that the fuel would be burned completely within an allowable duration even in lean-fuel conditions.

It was reported in 1963 [2] that a spark was created by focusing high-power laser in a gaseous medium. Since the 1970s, a high-power laser has been used as an ignition device for laboratory experiments [3,4]. Furthermore, laser-ignition technology has recently been under development as a new practical spark-ignition technology [5–9]. Although laser ignition needs an optical access to the chamber, it can induce higher-energy ignition at higher pressures without erosion as compared to conventional spark plugs. In addition, high flexibility in the timing and placement of ignition is often emphasized as the principal advantage of laser ignition [5] facilitating the combustion of lean-fuel mixtures.

For the ignition ability of a laser-induced spark, it is known that the minimum ignition energy (MIE) obtained by laser ignition is greater than the MIE obtained by a conventional electrical-spark ignition for a wide range of equivalence ratios [10]. However, in some lean-fuel conditions with high MIE, the higher ignition ability of the laser as compared to electrodes has been demonstrated [10,11]. Although the higher ignition ability of the laser may be partly due to the lack of heat loss to the electrodes [5], detailed mechanisms that explain the higher ignition ability are unavailable.

In this study, in order to explain the reasons for the higher ignition ability of a laser-induced spark in lean-fuel conditions, laser-spark and conventional electrical-spark ignition systems were comparatively studied by experiments in which the deposited energies were the same in both cases. It was found that the higher ignition ability of a laser-induced spark was due to the augmentation of the effective ignition energy by the rapid heat release from the combustible mixture sucked into the initial flame kernel by a non-spherical inward flow created by laser-induced gaseous breakdown as well as due to the lack of heat loss to electrodes. Furthermore, the influence of a newly developed technology for the reinjection of the transmitted laser light into plasma [12] on the ignition

* Corresponding author.
*E-mail address:* takumaendo@hiroshima-u.ac.jp (T. Endo).

http://dx.doi.org/10.1016/j.combustflame.2017.01.016

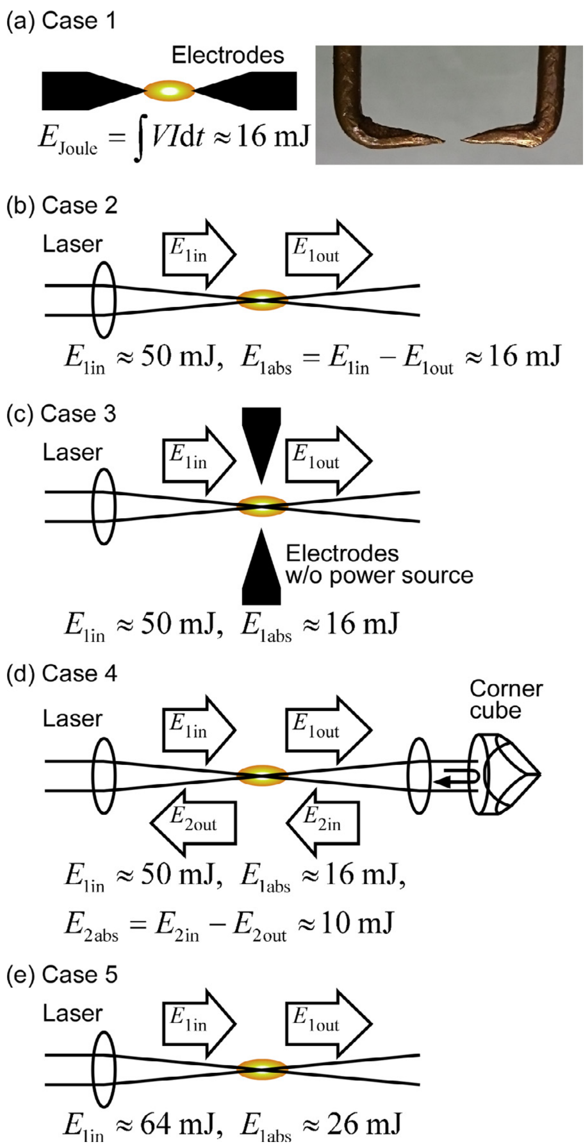


**Fig. 1.** Experimental arrangement.

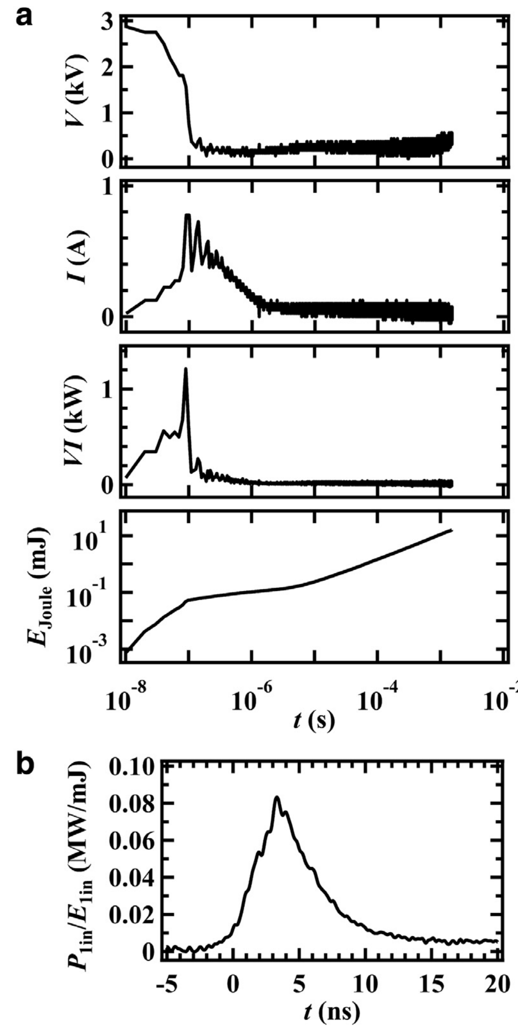


**Fig. 2.** Temporal profiles of ignitors. (a) Electrodes. (b) Laser.

ability was studied. This technology extended the lean limit of successful ignition owing to the increased total absorption efficiency, where differences in gas-dynamic processes had only minor effects.

## 2. Experimental arrangement

Figure 1 shows the schematic representation of the experimental arrangement for which five cases were investigated. Case 1 consists of the spark ignition induced by a pair of high-voltage electrodes that was built by us using copper rods of 2.6 mm in diameter, and a gap size of 1.3 mm. The spark was driven by an automotive spark-plug driver: 90919-02240 (TOYOTA). Figure 2(a) shows the temporal profiles of voltage $V$ measured using a high-voltage probe: P6015A (Tektronix); and current $I$ measured using a current probe: CT-B0.5 (Magnelab). It also shows the power $VI$, and deposited energy, $E_{Joule} = \int_0^t VI dt$, where the time origin $t = 0$ corresponds to the beginning of the electrical breakdown. The time duration of the energy deposition was approximately 1.5 ms. In Case 2, the spark ignition induced by a 1064-nm laser: LS-2131M-10 (LOTIS TII) was observed. The temporal profile of an incident laser pulse is shown in Fig. 2(b), where $E_{1in}$ and $P_{1in}$ are the incident energy and power, respectively. The pulse duration, defined by the ratio of $E_{1in}$ to the peak of $P_{1in}$, was approximately 12 ns. The effective diameter of the focal spot was approximately 68 µm. The details of the optical arrangement are described in [12]. Case 3 consists of laser ignition with dummy electrodes. The objective of Case 3 experiments was to examine the effect of heat loss to electrodes on the ignition ability. Case 4 consists of a laser ignition with reinjection of transmitted laser light into plasma using a corner cube [12]. The transmitted laser light was reinjected into the plasma with an 8-ns delay as compared to the incident laser pulse. Case 5 was laser ignition with increased energy. The incident energy in Case 5 was adjusted so that the absorbed energy was the same as the total absorbed energy in Case 4. In all the experiments on laser ignition, the incident energy $E_{1in}$, the transmitted energy of the incident laser pulse $E_{1out}$, and the transmitted energy of the reinjected laser pulse $E_{2out}$, if necessary, were simultaneously measured using three identical energy meters: PE 25-C (OPHIR) and beam splitters. The energy of the reinjected laser pulse $E_{2in}$ was evaluated from $E_{1out}$ and the net reflectivity of the optical components for light reflection including a corner cube measured in advance.

In the experiments, a quiescent propane–air premixed gas, in which the mole fraction of propane was varied between 2.3 and 3.0%, was ignited in a constant-volume chamber initially at the absolute pressure of 100 kPa and at room temperature (approximately 20 °C). The chamber was made up of duralumin, and the