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Comparative study of laser ignition and spark-plug ignition in high-speed flows

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ABSTRACT

Laser ignition and spark-plug ignition were experimentally compared in high-speed ethylene-oxygen mixture flows of up to approximately 100 m/s. Nd:YAG laser of 12-ns pulse duration and a semi-surface-discharge-type spark plug of 1.8-ms discharge duration were used to conduct the experiments with deposited energy of approximately 24 mJ in both cases. The self-emission was observed by a high-speed camera. The flame-spread behavior and ignition ability were examined in lean-fuel conditions. The study findings revealed that laser ignition was superior to the spark-plug ignition in the aspect of the early-stage rapid flame spread, although it showed lower probability of successful ignition than that by the spark plug near the lean-fuel ignitable limit. These findings suggest that the ignition in high-speed flows is significantly influenced by the turbulence via the enhancement of heat transport in particular.

1. Introduction

Currently, the ignition process in most of the spark-ignition combustors is initiated by gaseous breakdown between a pair of high-voltage-applied electrodes. Such ignition schemes involve leaner fuel mixtures that require larger discharge energy, and higher initial pressure that requires higher voltage to be applied to the electrodes; both of which result in enhanced erosion of the electrodes and shorten the lifetime of the spark plug [1].

It has been known since 1963 that gaseous breakdown can also be realized by focusing a high-power laser beam in a gaseous medium without a pair of electrodes [2]. In addition, the high-power laser has been used as an ignition device in laboratory experiments since the 1970s [3,4]. Subsequently, the advancement in high-power laser technology has led to the recent emergence of the laser-ignition systems as a new practical spark-ignition technology [5–9].

The purpose of this study is to compare the characteristics of laser ignition to those of the conventional spark-plug ignition systems that are widely used around the world. When considering the ignition ability of a laser-induced spark, it is known that the minimum ignition energy (MIE) of the laser ignition is higher than that of the conventional spark-plug ignition for a wide range of equivalence ratios [10]. However, in some lean-fuel conditions of high MIE, higher ignition ability of a laser-induced spark compared to that of an electrode-induced spark has been demonstrated [10,11]. Recently, the ignition ability of a laser-induced spark was compared with that of an electrode-induced spark using the same deposited energy into quiescent lean-fuel propane-air mixtures [12]. This study showed that the ignition ability of a laser-induced spark was higher than that of an electrode-induced spark near the lean-fuel ignitable limit. This behavior was attributed not only to the lack of heat loss to electrodes but also to the large initial flame kernel. The effective energy contained in the large initial flame kernel was augmented by the rapid heat release from the combustible mixture sucked into the kernel by a non-spherical inward flow that was created by the laser-induced spark.

As a result of past investigations, the characteristics of laser ignition in a quiescent gas mixture have become understood to some degree. However, an actual gas mixture in a practical combustor is not quiescent when it is ignited. For example, in a reciprocating engine, the mean and fluctuating velocities of 1 to 10 m/s are obtained in the clearance volume at the top-center crank position [13]. In a scramjet engine, ignition in a combustible gas flow of approximately 2000 m/s is required [14]. Apart from internal combustion engines, a high-frequency pulse detonation combustor developed for thermal spray requires a combustible gas flow of approximately 100 m/s to be ignited [15].

The influence of flow on the characteristics of spark ignition induced by a pair of high-voltage-applied electrodes has been studied for more than half a century [16–19]. It has been reported that both the flow speed itself and the turbulent nature of the flow

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have significant influence on the ignition characteristics. Limited research that examines the characteristics of spark ignition induced by laser in a flowing medium has been conducted [20–22]. Specifically, to the best of the authors knowledge, no experimental study has been conducted to compare the characteristics of laser ignition with those of spark-plug ignition in a flowing medium using the same deposited energy.

When the ignition of a combustible gas mixture flowing at the speed of approximately 10 m/s is considered, the initial flame kernel is moved and/or deformed several millimeters in several hundred microseconds. This means that the initial flame kernel experiences movement and/or deformation comparable to its own size during its growth to the self-propagating flame. In such cases, both the heat loss to electrodes in a conventional spark-plug ignition and the flow driven by a laser-induced spark must be largely different from those in quiescent media cases. Therefore, it is important to clarify the characteristics of laser ignition in flowing media in comparison with those of spark-plug ignition using the same deposited energy.

At the end of Introduction, the difference between laser ignition and spark-plug ignition is briefly described. Basically, a gaseous medium is ignited by thermal and/or chemical effects of a tiny plasma, which is usually called a spark. In laser ignition, a spark is created in a gaseous medium by laser-induced breakdown. For realizing the laser-induced breakdown in a gaseous medium, the laser power density of the order of more than 10^{11} W/cm^2 is needed when the duration of a laser pulse is longer than a nanosecond. This breakdown threshold in a gaseous medium is usually much higher than that on the surface of a solid material. Therefore, the laser beam should be focused apart from the surface of the glass window through which the optical access of the laser beam to the combustion chamber is realized. Otherwise, the surface of the glass window is damaged. In some cases, the laser beam is focused on the surface of the inner wall of the combustion chamber, and a spark is created on the solid surface. In this laser-ignition scheme, the laser power density needed for creating a spark is much lower than that in the case of the laser-induced breakdown in a gaseous medium because of much lower breakdown threshold. However, the laser-irradiated solid surface is ablated and a hole is bored there. Accordingly, this scheme is usually considered different from the ordinary laser ignition. Another characteristic of laser ignition forced by the high breakdown threshold is the short pulse duration. Because the size of the focal spot of a laser is usually of the order of 10 μm, the duration of a laser pulse, whose energy is of the order of 10 mJ, needs to be less than the order of 100 ns for realizing the laser-induced breakdown in a gaseous medium. On the other hand, in spark-plug ignition, a spark is created between a pair of electrodes when the electrical voltage applied to the electrodes is higher than a certain threshold. Therefore, the spark is created essentially near and on the solid surface. In spark-plug ignition, the duration of the electrical pulse applied to the electrodes is arbitrary in principle. However, if the pulse duration is too short, the electrical current becomes too large, and accordingly the lifetime of the electrodes becomes too short due to erosion. Therefore, the duration of the electrical pulse applied to the electrodes is usually of the order of a millisecond in the practically-used spark plugs. In summary, the duration of the energy deposition in laser ignition is shorter than that in spark-plug ignition more than four orders in magnitude, and a laser-induced spark is created apart from any solid surface while a pair of high-voltage-applied electrodes creates a spark near and on the electrodes.

In this study, the characteristics of laser ignition and conventional spark-plug ignition were compared in high-speed flows of up to approximately 100 m/s using the same deposited energy. Ethylene–oxygen gas mixtures were used with a geometrical arrangement similar to that of a high-frequency pulse detonation combustor [15]. The advantage and disadvantage of laser ignition in comparison with conventional spark-plug ignition were disclosed. The study findings revealed that the laser ignition exhibited the advantage of rapid flame spread; however, it showed lower probability of successful ignition than that by the spark plug near the lean-fuel ignitable limit.

2. Experimental arrangement

Figure 1(a) shows a general view of the experimental setup. The combustor was a straight rectangular channel the cross-sectional area of which was the same as that of a circular tube, whose inner diameter was 10 mm, which was the combustor of a high-frequency pulse-detonation thermal-spray gun [15]. This geometrical arrangement was adopted because of its simpleness. Ethylene and oxygen were mixed at the right end of the rectangular channel as head-on colliding jets from nozzles of 3 mm in diameter. The flow rates of ethylene and oxygen were independently controlled by both of their supplying pressures and orifice diameters. These parameters were selected based on the data obtained from the preliminary experiments in which the flow rates of ethylene and oxygen were measured as functions of their supplying pressures and orifice diameters. The preliminary experiments confirmed that the total flow rate from both gas-supplying pipes was the sum of the flow rates from the respective gas-supplying pipes under some conditions. Nitrogen was used to purge the residual gas from the combustor. In the ignition experiments, the magnetic valves began to close 5 ms after the beginning of the breakdown so that the ignition and subsequent flame spread occurred in a high-speed flow.

Figure 1(b) shows the experimental setup of the spark-plug ignition. The spark plug used in the experiments was the semi-surface-discharge type (NGK R847-11), which was driven by an automotive spark-plug driver: 90919-02240 (TOYOTA). As shown in Fig. 1(b), only the center electrode of the spark plug, whose diameter and thickness were respectively 1.6 mm and 0.6 mm, protruded from the inner surface of the flow channel. The temporal waveforms of voltage and current of the electrical spark were measured in the quiescent atmospheric air in advance using a high-voltage probe: P6015A (Tektronix) and a current probe: CT-B0.5 (Magnelab), respectively. The deposited energy was calculated to be approximately 24 mJ, where the duration of the discharge was approximately 1.8 ms. In the ignition experiments, the spark plug was driven under the same conditions as that of the preliminary measurements carried out in the quiescent atmospheric air, although the temporal waveforms of voltage and current of the electrical spark in the high-speed gas flows were rather disturbed compared with those in the case of the quiescent atmospheric air. The observed disturbances might be attributed to the multiple discharges due to the high-speed gas flows [17]. In fact, self-emission images showing the rebuilding of the discharge path were observed in some cases, as shown in Fig. 2(b).

Figure 1(c) shows the laser ignition experimental arrangement. The laser system used in the experiments was a multimode Q-switched Nd:YAG laser: model LS-2131M-10 (LOTIS TII) with pulse duration of approximately 12 ns [23]. The laser beam diameter was expanded from 5 to 40 mm before focusing. An aspherical plano-convex lens with a focal length of 37.5 mm was used for focusing the laser beam at the center of the channel. Based on the past experimental data [23], the effective diameter of the focal area was estimated to be approximately 12 μm as it was assumed to be proportional to the focusing *F* number. The absorption efficiency of the laser pulse was measured in advance as a function of the incident energy, where the channel was filled with ethylene-oxygen gas mixtures of various equivalence ratios and flow speeds. In the ignition experiments, the incident energy of the laser pulse was