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Flame kernel formation behaviors in close dual-point laser breakdown spark ignition for lean methane/air mixtures

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Abstract

Ignition behaviors of close dual-point laser breakdown spark ignition were investigated experimentally for methane/air mixtures at 0.1 and 1.0 MPa in a constant volume combustion vessel. Absorbed energy was measured from the difference between incident and transmitted laser rays using two joule meters as the ignition energy, and the behaviors of the initial flame kernel were observed with Schlieren photography using a high-speed video camera. First, the ignition behaviors of a single-point laser breakdown spark ignition were investigated. The results indicated that the effect of the focusing lens on the minimum ignition energy (MIE) was limited in terms of the absorbed energy. Although the MIE at 1.0 MPa was lower than that at 0.1 MPa near the stoichiometric equivalence relationship was reversed near the lean limit. For lean mixtures, local quenching of the initial flame kernel was clearly observed including third lobe region especially at 1.0 MPa. In the case of the close dual-point sparks for an equivalence ratio of 0.6, formation of a third lobe was suppressed. When the dual spark gap was large, two flame kernels were formed as observed in the case of the single spark. An optimal gap in which the absorbed energy was minimal for successful ignition existed depending on the pressure, although the magnitude of the associated energy was not so different from that in the case of the single spark. However, the growth rate of the initial flame kernel formed by the close dual sparks was considerably higher than that formed by the single spark, especially at 1.0 MPa. Enhancement of the flame kernel development due to the close dual spark was clearly observed.

Keywords: Laser breakdown spark ignition; Lean mixture

1. Introduction

To increase the thermal efficiency of spark ignition engines, reducing cooling loss is one of the promising methods when using lean mixture combustions. For lean mixtures, the minimum ignition energy (MIE) is high, and the flame speed

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is low. To increase in the flame speed, combustion in high tumble and high turbulent flows is required although it is difficult to ignite the mixture in such an environment. Ignition is the initiation process of combustion, and it influences the subsequent flame propagation. It is a rather important stage both fundamentally and practically in combustion science. Electrical spark ignition has been studied widely, and the MIE for fuel mixtures has been measured as a useful parameter for investigating the ignition process [1,2]. It has been reported that MIE is largely influenced by electrode geometry [1,3,4] and energy deposition profile [5]. In the case of electrical spark ignition, ignition position is anchored in the electrode gap, and heat loss to the electrode seems to be non-negligible. To get rid of the influence of the electrode, laser-induced spark ignition has been investigated widely. Laser-induced sparks can form plasma kernels at the desired time and position. Although the breakdown threshold voltage increases with an increase in pressure in the case of an electrical spark, the threshold of laser energy decreases in the case of the laser breakdown spark [6]. Laser breakdown spark ignition is similar to conventional electrical spark ignition, although their breakdown processes are different [7]. Moreover, the MIE of laser-induced spark ignition has been measured by a number of researchers [8–12]. Although pulse width and wavelength influences the breakdown threshold, their influences are not significant in terms of ignition energy [13,14]. Laser breakdown spark ignition has been investigated in laminar flows and MIE has been measured [15,16]. Moreover, ignition experiments for lean mixtures in turbulent flows have been conducted, and MIE has been measured [17]. Although it is free from heat loss to the electrode, the MIE of a laser-induced spark is substantially higher than that of an electrical spark [8–11,15]. The short-term deposition of energy input seems to result in fast energy dissipation in the early stages of flame kernel formation. In contrast, it has been reported that the lean limit of ignition in engines is extended by laser breakdown sparks [12,18]. To consider energy dissipation in laser ignition, Phuoc investigated the energy loss due to radiation and shock propagation in laser spark ignition [19]. In addition, laser-induced spark ignition has been modeled [14,20,21], and knowledge on the interactions among plasma formation, energy absorption, and gas dynamics have been obtained. The initial plasma formed by laser irradiation is ellipsoidal, and its size is influenced largely by the composition of the mixture [8,14,20]. After the initial plasma is formed, the initial hot kernel shows a unique behavior, namely, third lobe formation [21,22]. Figure 1 shows a gas dynamics of the third lobe formation. The laser energy is absorbed by the plasma ellipsoid formed by the breakdown, and energy is absorbed near the leading edge than that near the trailing edge. Two pairs of vortices are formed near the leading and trailing edges of the plasma kernel. Owing to the gas dynamics induced by the unbalanced pairs of vortices, the initial hot kernel grows toward to the laser incident direction after the laser emission [22]. The formation of the third lobe has been investigated numerically, and the associated gas dynamics is formed by non-uniformed laser absorption [21]. Formation of the third lobe seems to accelerate the flame kernel formation for reactive gases as is the case for stoichiometric mixtures. In contrast, rapid expansion of the third lobe seems to result in local quenching and energy dissipation near the ignition limit, especially for less reactive mixtures. To control the direction of third lobe formation, the combinations of nano- and femto-second lasers are shot orthogonally [23].

For lean mixtures, because flame propagation speed is unacceptably slow [14], flame propagation distance can be shortened using multi-point laser sparks [24]. Multi-point laser ignitions have been tested for lean mixtures. A multi-point laser ignition technique using two conical cavities has been suggested, and significant reduction in combustion time has been achieved [25]. A multi-point laser spark generation using a spatial light modulator has been suggested, and the formation of multiple plasmas on a plane and an axis have been realized in air [26]. In these reports, multiple plasmas have been used to reduce flame propagation length, and the separated flame kernels have been formed.

In the present study, we developed a dual-point laser ignition technique to suppress energy dissipation and local quenching, especially for lean mixture combustions. In our method, close dual-point sparks are generated for fusing two initial flame kernels in the early stage of flame kernel formations. We tested close dual-point laser ignition for methane/air mixtures at 0.1 and 1.0 MPa in a combustion vessel. In the present study, especially for mixtures near the lean limit, we investigated experimentally the ignition behavior of close dual-point laser breakdown spark ignition. The resulting ignition characteristics and ignition performance are discussed in this paper.

2. Experimental

Experiments were performed using a constant-volume combustion chamber. A schematic of the experimental setup is shown in Fig. 2. Combustion experiments were performed in a chamber made of A7000 aluminium alloy; the chamber had 5 optical quartz windows on its flanges. Methane/air mixtures were prepared in a mixing tank made of SUS 304 stainless steel, and the mixtures were stirred continuously. Mixture concentrations were determined using pressure sensors with the full scales of 101.3 kPa (KEYENCE, AP-C30), 1 MPa (KEYENCE, AP-C33) and 10 MPa (KEYENCE,