Combustion and Flame 165 (2016) 334–345

Contents lists available at ScienceDirect

Combustion and Flame

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

Simultaneous optical ignition and spectroscopy of a two-phase spray flame

Seok Hwan Lee[a], Hyungrok Do[b], Jack J. Yoh[b,*]

[a] Division of Physical Metrology, Korea Research Institute of Standards and Science, 267 Gajeong-ro, Yuseong-Gu, Daejeon 34113, South Korea
[b] Department of Mechanical and Aerospace Engineering, Seoul National University 1 Gwanakro, Gwanakgu, Seoul 151-744, South Korea

A R T I C L E I N F O

Article history:
Received 26 August 2015
Revised 16 December 2015
Accepted 16 December 2015
Available online 16 January 2016

Keywords:
Spray
Laser induced plasma spectroscopy
Ignition
Droplet

A B S T R A C T

Simultaneous laser ignition and spectroscopy is a scheme that enables rapid determination of the local equivalence ratio and condensed fuel concentration during a reaction in a two phase spray flame. In parallel with laser ignition, the equivalence ratio and droplet characteristics such as the concentration, size, and distribution of spray combustion are simultaneously obtained for a feedback control system. The plasma characteristics of fuel droplets are evaluated initially by shadowgraph, and the high-speed imaging of air and spray breakdown provides visualization of the transition from the plasma to a flame kernel. The spectrum in the spray is evaluated according to droplet characteristics such as size and number density. The probability density function is used to analyze the interaction between the fuel droplets and the laser plasma with laser-induced breakdown spectroscopy (LIBS) measurements. In this paper, we have conducted quantitative analysis of the LIBS signals according to the equivalence ratio, droplet size, droplet number density and droplet concentration for development of a control strategy for flame ignition and stabilization with simultaneous in situ combustion flow diagnostics.

1. Introduction

Spark-ignition (SI) engines based on direct injection (DI) promise significant advantages in terms of thermal efficiency and power output, and present a means of overcoming problems related to knocking, backfiring, and preignition. Although spark ignition is standard for automotive engines, there are disadvantages associated with the use of electrical spark plugs. The ignition location is restricted to the electrode gap, and energy loss occurs since the plug is a heat sink and interacts with the flow field. Varying the ignition energy is restricted by the low repeatability. The ignition reliability of electric spark plugs eventually declines due to carbon fouling, which is the most common spark plug related failure.

Laser-induced breakdown in the fuel-air mixture has been studied for several decades with recent notable attempts to overcome the weaknesses of spark ignition [1–6]. Although laser system has some shortcomings such as relatively high cost and low reliability in a harsh environment, laser ignition as opposed to spark ignition has advantages such as i) no need of a spark plug, ii) precise triggering, iii) a flexible selection of fuel breakdown locations and immediacy, iv) wide range of ignition energy (30–300 mJ), and v) good reproducibility.

Laser ignition in gas phase fuel has been studied by many researchers in the past with a notable review article by [7], whereas, research on laser ignition for two-phase flow is less common. Laser-induced spray ignition has been explored for reciprocating engines [8,9] and aviation engines [10,11]. Laser ignition has benefits for reciprocating engines and aviation gas turbines due to the ability to adjust the ignition position and to generate multiple ignition. Moreover, laser ignition can generate reliable ignition of lean mixtures, which has high potential for applications in lean premixed prevaporized combustion [10].

On the other hand, the ignition process in DI engines is time dependent and complex, since it is greatly influenced by many factors such as the local fuel equivalence ratio, gas density and condensed-fuel concentration. The local equivalence ratio near the ignition position at the time of ignition is particularly important for successful ignition due to a stratified fuel concentration near the ignition position. Also, the location of the ignition source is critical for flame ignition and stabilization particularly in turbulent non-premixed environments because flow properties significantly affecting the flame ignition processes vary in space. Therefore, picturing the inhomogeneous distributions of the flow

* Corresponding author.
E-mail address: jjyoh@snu.ac.kr, jjyoh1@gmail.com (J.J. Yoh).

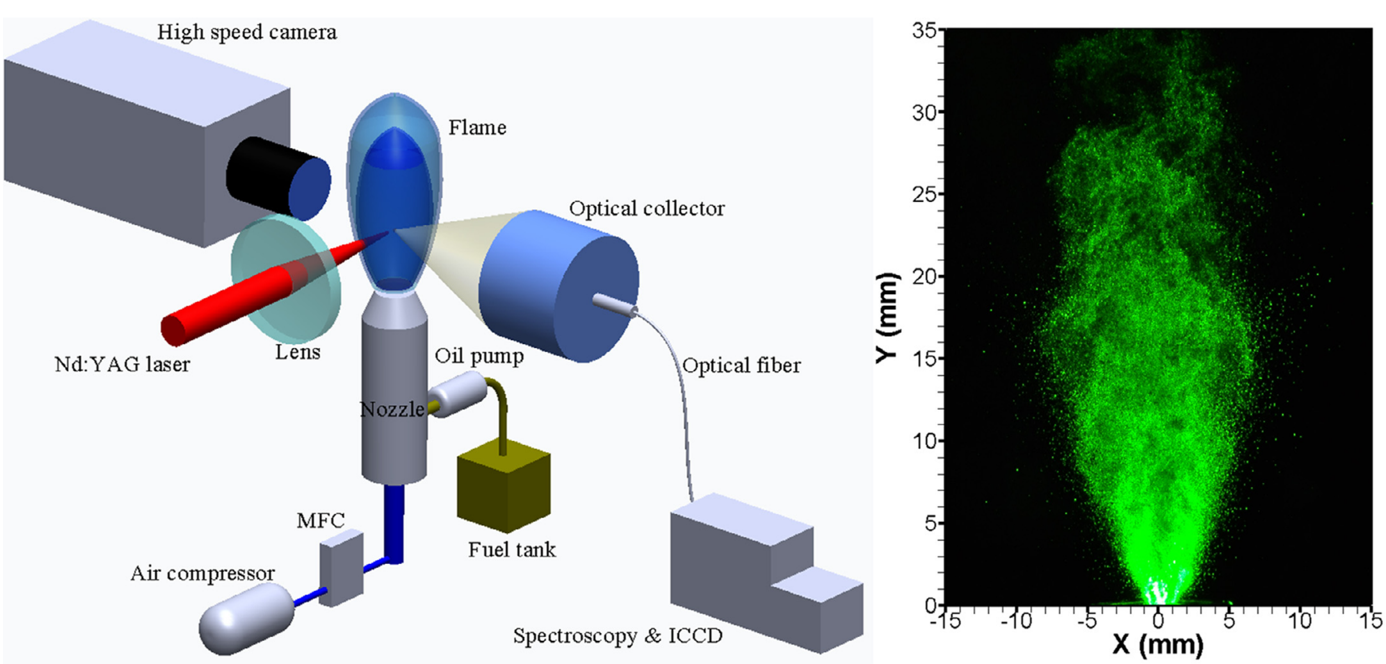
http://dx.doi.org/10.1016/j.combustflame.2015.12.016

properties is essential in understanding the ignition processes in two phase spray flame. Nevertheless, measurements of these properties are challenging: only non-intrusive optical measurements methods are viable under the harsh flow conditions.

A variety of optical techniques have been used previously to measure the local equivalence ratio, including infrared (IR) absorption, planar laser-induced fluorescence (PLIF) [12], and Raman scattering [13]. Spontaneous Raman scattering and coherent anti-Stokes Raman spectroscopy can provide species concentration and gas temperature/density. However, the Raman signal is very weak and is thus susceptible to fluorescence/emission interferences. Furthermore, the complexity of pulsed Raman scattering measurement may limit its application in laboratory environments. Alternatively, laser-induced breakdown spectroscopy (LIBS) has high potential in combustion applications due to its high emission intensity and minimal system complexity. Ferioli et al. [14] used LIBS on engine exhaust gas to illustrate the ability of this technique to measure the equivalence ratio of SI engines. LIBS was successfully applied to understand the mixture dynamics inside a turbulent premixed combustor with strong pressure oscillations in Ref. [15]. Do et al. measured fuel concentration and gas density simultaneously in a supersonic wind tunnel using LIBS [16]. In [17], a two-dimensional LIBS was proposed as a meaningful diagnostic tool for flame analysis.

Measuring fuel properties such as equivalence ratio and liquid phase fuel volume fraction at possible ignition and/or flame residence locations in a SI engine is key for executing a feedback control strategy since the properties can potentially suggest optimal ignition/stabilization locations under harsh combustor conditions. Focused laser energy can also be used as a tool for successful ignition and to aid flame enhancement at preferred locations. Only a few limited studies on such feedback control are reported. Roy et al. used spark-induced breakdown spectroscopy (SIBS) to measure the local fuel-air concentration in the spark gap at the time of ignition under stratified-charge conditions [18]. Phuoc [19] used a laser-induced spark to measure the ignition and fuel-to-air ratio of CH_4-air and H_2-air combustible mixtures simultaneously. The combinded laser induced ignition and plasma spectroscopy was used for measuring equivalence ratio at the ignition point and time in a partially premixed hydrogen-air burner [20]. Also Joshi et al. [21] used a natural gas engine to demonstrate the simultaneous laser ignition and LIBS equivalence ratio measurement.

In mostly gas phase, the laser ignition and spectroscopic measurement have been conducted in reacting flows. The characteristics of laser-induced breakdown and spectrum in two phase flow are vastly different from those in the gas phase [11]. Understanding of the interaction between laser-induced breakdown and fuel spray is needed for laser ignition and quantitative measurement of fuel concentration. Therefore, the primary objective of this study is to investigate flame ignition processes in two-phase hydrocarbon fuel spray with simultaneous measurements of equivalence ratio and liquid phase fuel concentration. An unprecedented investigation of laser-induced ignition is conducted in the spray flame with high-speed imaging in conjunction with quantitative and simultaneous flow property measurements using LIBS. Three atomic and molecular emission line intensities (H-α (656 nm), O (777 nm) and C_2 (516 nm)) are monitored, which potentially provide better accuracy in the species concentration measurements. The idea behind the present study is a combination of laser ignition and spectroscopy for feedback control of fuel injection. This is a desirable scheme since such real time information onboard an DI engine for instance can be constantly monitored and fed back to the control loop to improve the mixing process and minimize emission of unwanted species and combustion instability, preventing the degradation of vehicle performance. Monitoring of these instantaneously varying flow properties would be desirable particularly for the incipient vehicle acceleration period when the combustor flow enthalpy is insufficient to initiate and sustain stable combustion reactions, thus requiring a systematic feedback control strategy. Furthermore, the compact design of such system would allow a small sized single pulsed laser to be used for both pulsed ignition and breakdown spectroscopy. Laser technology has advanced significantly: compact diode-pumped solid-state (DPSS) laser or compact fiber laser, and broadband spectroscopy can meet such compact and low-power requirements for realtime diagnostics of the combustor, for instance. In essence, the use of one small laser for



(a) (b)

Fig. 1. (a) Experimental setup and (b) scattering image of the droplet.