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Towards simplified monitoring of instantaneous fuel concentration in both liquid and gas fueled flames using a combustor injectable LIBS plug

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ABSTRACT

In this study, instantaneous measurement of fuel concentration and flame diagnostics in both liquid and gas hydrocarbon fueled flame is presented using a simplified laser-induced breakdown spectroscopy (LIBS) approach. The newly developed device or hereinafter the “plug” receives specified lines from the plasma emission without resorting to the conventional LIBS system. Bandpass filters and photodiodes were mounted in the plug to capture hydrogen (656 nm) and oxygen (777 nm) atomic lines. Since H/O intensity ratio has a linear relationship with fuel concentration, the plug's calibration curve between equivalence ratio and H/O intensity ratio is constructed. Single phase and two-phase hydrocarbon fuel fields were measured with the device using gasoline (liquid) and LPG (gas). With the advantage of simplicity of the plug, multiple plasma points and plugs were simultaneously applied in the fuel field and showed possibility of using a single laser device to construct multi-points concentration mapping. Also, flame diagnostics scheme was proposed based on the observed difference of intensity duration between reactive and non-reactive fuel fields.

1. Introduction

Fuel concentration and flame distribution have a close relationship with stable combustion in an operating engine. Especially in high-speed combustors, because of their unpredictability and susceptibility, measuring instantaneous flow characteristics without interrupting the flow has been one of the biggest issues of interest in the current combustion studies [1]. To overcome disadvantages of existing measurement methods, such as physical interruption of instruments and slow response time, optical measurement techniques have been developed and adopted as combustor diagnostics [2–4]. Especially for high-speed engines such as scramjet engines, studies related to fuel injection and mixing are major concerns since the flow residence time in combustor is of the order of a few milliseconds [5]. In order to promote and verify fuel mixing in scramjet engines, both experimental and computational studies including designing of cavity flame holders have been conducted and identified their flow behaviors [6]. However, as these methods are aimed at predicting the flow inside a combustor, a real-time diagnosis of fuel distribution inside an operating combustor was not possible. Furthermore, in a highly turbulent flow, experimental measurements or computational predictions were not reliable due to unaccountable flow dynamics variables. This limitation calls for the need for instantaneous measurement inside the actual engines.

This study proposes a method of instantaneous detection of fuel concentration in either liquid or gas phase hydrocarbon fuel for flame diagnostics using a simplified laser-induced breakdown spectroscopy (LIBS) device. LIBS has been widely used to instantaneously detect various elements in severe environments utilizing a simple system configuration. A concentrated laser excites molecules and generates plasma at one point. Excited ions and electrons return to their ground states as the plasma cools down, and emit light with respective atomic frequencies. In the conventional LIBS system, plasma emission is collected with spectrometer and ICCD camera and analyzed to give whole spectra of atomic lines for measuring properties such as density and the equivalence ratio of hydrocarbon fueled flames [7]. Also, it is known that H/O intensity ratio obtained from LIBS has a linear relationship with equivalence

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ratio for given temperature and calibration curves were made [8–10].

Even though these earlier studies were aimed at understanding the hydrocarbon reacting flow, the conventional LIBS system had limitations in determining the fuel properties of the environment inside the real operating engine. As those aforementioned studies are mainly focused on constructing and validating relationships between hydrocarbon fuel distribution and LIBS signals, the present study is aimed at developing a simplified instantaneous measurement device that is intended to be installed in an operating combustor. To reduce the excessive volume of the configured spectrometer and ICCD camera, only a set of specific spectral signals was extracted from plasma. As H/O intensity ratio showed linear relationship with equivalence ratio, only H and O signal intensities were selected. The LIBS plug consisted of lens, two bandpass filters for hydrogen as well as oxygen, and two photodiodes. Plasma emission obtained from the plug is immediately changed to electric signal from photodiodes and was transmitted to an oscilloscope. This direct transmission of signal intensity made the delay time designation procedure simple.

The main purpose of the study is the instantaneous detection of hydrocarbon-air mixture in both reacting and inert environment using the LIBS plug. The instantaneous detection is especially attractive in high-speed air-breathing engines while providing a simultaneous feedback control for performance enhancement. Such concept is aimed at advancing the field of combustion where the fuel mixing and flame stabilizing at a high-speed condition are still considered challenging. In this study, calibration curves between the plug's signal and equivalence ratio of gasoline-air mixture and LPG-air mixture were newly established. Analysis of two-phase spray fuel field and single phase fuel field was done with our LIBS plug with gasoline and LPG as the target fuel, respectively. The simple construction of our LIBS plug enabled simultaneous measurements at multiple points. The simultaneous four-point measurements of the fuel distribution were done with an extended experimental setup using 4 plugs, which was not possible with the conventional LIBS setup. This brought a new possibility in application of LIBS in the two-dimensional flame diagnostics. Finally, using a continuous signal of the LIBS plug, identifying how long the plasma continuum emission lasts became possible. Collecting data immediately after plasma continuum emission in just a single shot was possible with a new LIBS plug. This is, not possible by using conventional LIBS setup, since it collects the accumulated intensity along ICCD exposure time. Also, since the decay time of signal intensity changed under two distinct flow conditions, it was possible to identify the difference of the plug's signal between reacting and non-reacting flow.

2. Experimental setup

2.1. Conventional LIBS setup

Fig. 1 shows conventional LIBS system setup. Nd:YAG laser (Surelite III, Continuum) with wavelength of 1064 nm and pulse duration of 5 ns was used to generate plasma. Plasma emission was collected with optical collector and optical fiber and then sent to spectrometer (Andor Mechelle 5000). ICCD camera (Andor iStar) collects separated lights with respect to its wavelength. In reacting flow, the conventional LIBS setup was used to validate LIBS plug's signal. Liquid gasoline was sprayed with air by a siphon nozzle (Delavan 30609-2). Spray angle of the siphon nozzle is 40° at 15 cm above the nozzle. The fuel flow rate was controlled with dosing pump (Simdos 10, KNF) with an accuracy within ±2% and is fixed at 0.17 cm^3/s. A pulsation damper (FPD 10, KNF) was attached to remove pulsation and provide continuous transfer of the flow. Air flow rate was controlled with Mass Flow Controller (MFC, TSC-230, MKP) which has accuracy of ±1% and is fixed at 166.67 cm^3/s.

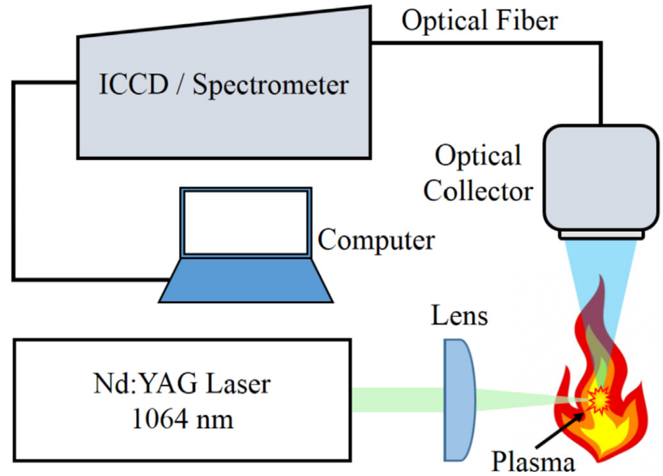

Fig. 1. Conventional LIBS setup.

2.2. LIBS plug implementation and setup

The simplified LIBS plug was designed and produced in this study, a device to acquire data on hydrocarbon fuel distribution and flame without using the bulky spectrometer and ICCD configuration, necessary for a conventional LIBS experiment. In our previous study, the concept of LIBS plug was validated with photodetectors and the initial test device was developed [11]. Though a possibility of the LIBS plug was demonstrated through a rough setup of the previous study, the enhanced LIBS plug's design was performed to acquire more accurate signal. In this follow-up research, the LIBS plug is presented and all data shown here are obtained with these small sized LIBS plugs. Two lens tubes (SM05V05, Thorlabs) were installed in the plug and its components were sealed in the tubes. Single lens tube had a diameter of 17.8 mm and a length of 26.2 mm. As other components were fixed inside, these two lens tubes determined the total size of the plug. Since H and O atomic lines from LIBS show a strong correlation with hydrocarbon fuel properties, the LIBS plug includes two bandpass filters which pass H atomic line (656.28 nm) and O atomic line (triplet at 777.194 nm, 777.417 nm, 777.539 nm) respectively. Fig. 2 shows the schematic of the plug setup. Bandpass filter (656FS10–12.5, Andover) with center wavelength (CWL) of 656 nm and full width at half

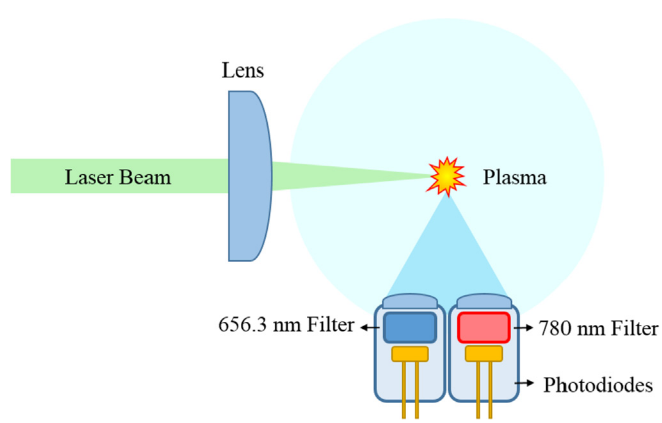

Fig. 2. A small-sized LIBS plug setup.