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Combined laser induced ignition and plasma spectroscopy: Fundamentals and application to a hydrogen–air combustor ☆

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Abstract

Combined Laser Induced Ignition and Plasma Spectroscopy (LI2PS) has the potential to give the exact local composition of a mixture at the ignition point and at the ignition time. However, as different laser energies are required to ignite a particular mixture as function of space, the typical approach using two power meters to calibrate the plasma spectroscopy measurement is not well suited. Furthermore, LI2PS requires single shot measurements and therefore high accuracy. In this paper, a novel calibration scheme is presented for application of Laser Induced Plasma Spectroscopy (LIPS) to gaseous analyses. Numerical simulations of air spectra are used to show that species emission can be used directly from the broadband spectra to determine the plasma conditions. The ratio of nitrogen emission around 744 nm and around 870 nm is found to be a sensitive indication of temperature in the emission ranging from 700 to 890 nm. Comparisons with experimental spectra show identical tendencies and validate the findings of the simulations. This approach is used in a partially-premixed hydrogen–air burner. First, helium is used instead of hydrogen. After an explanation of timing issue related to LIPS, it is shown that the calibration required depends only on nitrogen excitation and nitrogen–hydrogen ratio, without the need to know the deposited power. Measurements of the fuel distribution as function of injection momentum and spatial localization are reported. To illustrate the use of such a single shot approach, combined laser ignition and plasma spectroscopy is proposed. In this case, the calibration is based on hydrogen excitation and hydrogen–oxygen and hydrogen–nitrogen ratio. Results obtained with LI2PS show that ignition is successful only for high power and relatively high hydrogen concentration compared to the local mean. It is expected that LI2PS will become an important tool when dealing with partially-premixed or diffusion flame ignition.

Keywords: Laser Induced Plasma Spectroscopy; Species excitation; Numerical simulations; Experiments; Helium; Laser ignition; Partially-premixed flame; Hydrogen–air mixtures

1. Introduction

In combustion, an important quantity to measure is the ratio between fuel and oxidizer. This fuel–air ratio (or equivalence ratio) indicates the type of combustion occurring. Lean cases correspond to fuel in a relatively low concentration compared to oxidizer and rich cases to the opposite situation. This equivalence ratio will have strong impact on overall performance of the combustor. In practice, different strategies exist to measure this ratio. A recent review on the possibilities is given in [1]. Among those, techniques like Raman–Rayleigh require high-energy from an elongated pulse to get a good signal [1]. The signal to noise ratio remains an issue when dealing with individual measurements, especially if soot particles exist which can cause unwanted optical breakdown. The required optical setup may be an issue and easier techniques should be investigated, possibly requiring less laser energy. One may take advantage of the fact that optical breakdown is easy to obtain to

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get quantitative measurements of the fundamental composition of the gas, in both burned and unburned regions.

Laser Induced Plasma Spectroscopy (LIPS also called Laser Induced Breakdown Spectroscopy or LIBS) for combustion measurements is not a new idea, as results were initially presented in the early 80's ([2]). Recently, some applications have been proposed to measure local equivalence ratio using LIPS ([3–6]). Many different strategies exist to relate emission from spectra and equivalence ratio. Usually, one emission related to the fuel and one emission related to the oxidizer is used. For instance, the ratio between the CN band (707–734 nm) versus the sum of the emission of nitrogen (around 744 nm) and oxygen (around 777 nm) has been discussed ([3]). Other possibilities include using hydrogen as fuel marker (like in [5]) for which hydrogen line at 656 nm versus oxygen line at 777 nm is used. This ratio is also favored in [6], certainly due to the high signal to noise ratio provided by the hydrogen emission, compared to the carbon emission. Of course, using hydrogen as fuel marker requires the additional acquisition of background spectra without introducing fuel, so as to measure the emission due to water vapor.

An important limitation of using LIPS in practical situations comes from the fact that the calibration seems to depend on the laser wavelength, pulse energy, focusing lens and so forth as reported previously [5]. One of the main issues is that below certain pulse energy, the ratio between atomic emission and equivalence ratio changes [5]. This may result in using relatively high laser pulses to avoid such fluctuations but then effects of shock wave from the plasma may interfere with the flow and may limit the acquisition frequency. Furthermore, one may want to reduce as much as possible the energy used in order first to improve the acquisition frequency, but also to limit problems linked with optical access. Spark energy is usually defined as being the difference in energy before and after the plasma as measured through two power meters. This may not be the best solution for practical situation involving windows. Therefore, other strategies should be developed to yield quantitative measurements, which do not require the measurements of laser pulses energy and this will be developed in the first part of this article.

Regarding combustion itself, in many situations, ignition remains an issue and one may want to develop alternative technologies, such as laser ignition. The reason for using laser ignition is the good control of ignition source (easily changeable with the focal length) as well as the absence of electrodes, and therefore reduced heat losses. As far as laser ignition is concerned, many publications have been reported for the case of perfectly premixed conditions (steady conditions under atmospheric pressure [4] or high-pressure [7], laminar [8] or under different levels of turbulence [9]). For further information, one may refer to a recent review [10]. Very few studies have reported the use of laser ignition in non-premixed conditions, one of the reasons being that the local equivalence ratio has to be measured simultaneously. Among those, Phuoc et al. [11] reported laser ignition measurement together with laser induced plasma spectroscopy applied to a hydrogen–air diffusion Bunsen type flame. Measurements of hydrogen to oxygen ratios were compared with ignition probability and relations between those two quantities were derived. Ignition was possible only within a range of this H to O ratio, however no quantification of the exact equivalence ratio was provided. Recently ([12]), some results were presented where both laser induced ignition and plasma spectroscopy were simultaneously used. The experiments were limited to an ignition cell for which uniform mixture was generated under different pressure (from 100 kPa to 500 kPa). Results indeed showed the possibility to simultaneously use laser as ignition and diagnostic source, even though those first results were obtained in a static ignition cell (hence premixed).

The present research aims at providing experimental measurements of equivalence ratio at the ignition point and time in a partially premixed hydrogen–air burner. The second section of this article describes the experimental setup, both the burner and the measurement techniques. The third section focuses on plasma properties, such as temperature and simulation of spectra is undertaken to find proper emission ratio that may be used as plasma temperature indicator. The fourth section presents concentration measurements obtained with helium, whereas the last part deals with hydrogen ignition, combined with equivalence ratio measurements. Finally, conclusions are drawn and perspectives given.

2. Presentation of the setup and the measurement techniques

For the development of a Mach 6 class turbojet engine, one of the candidates is a pre-cooled turbojet engine with liquid hydrogen as fuel [13]. Among the various restrictions, the size and mass are the most severe. In the present case, a reverse flow annular combustor is adopted. Because mixing has to be achieved within a small distance, fuel impingement is employed. Though the engine uses liquid hydrogen as fuel, the hydrogen is gasified before entering the gas-turbine combustor. Therefore for development purposes, gaseous hydrogen is directly used. A sketch of a single element (Fig. 1) is displayed as the present study limits itself to a single element. To allow optical access (for both ignition and LIPS), the sidewalls are made of glass. The outer part of the glass has a diameter of 27.5 mm with an inner

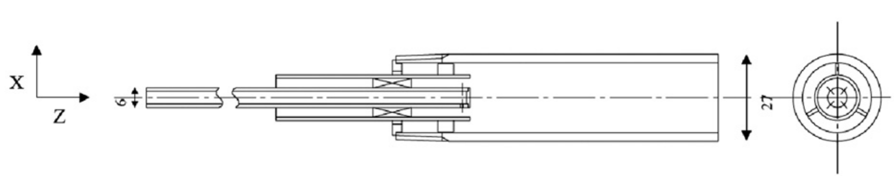

Fig. 1. Sketch of the hydrogen burner.