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Lean burn limit and time to light characteristics of laser ignition in gas turbines

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ABSTRACT

This work details a study of laser ignition in a low pressure combustion test rig, representative of an industrial gas turbine (SGT-400, Siemens Industrial Turbomachinery Ltd.) and for the first time investigates the effect of air mass flow rate on combustion characteristics at air/fuel ratios at the lean burn limit. Both the lean burn limit and time taken to light are essential in determining the suitability of a specified air/fuel ratio, especially in multi-chamber ignition applications. Through extension of the lean burn limit and reduction of the time taken to light, the operating window for ignition with regards to the air/fuel ratio can be increased, leading to greater reliability and repeatability of ignition. Ignition of a natural gas and air mixture at atmospheric pressure was conducted using both a standard high energy igniter and a laser ignition system utilizing a Q-switched Nd:YAG laser source operating at 1064 nm wavelength. A detailed comparison of the lean burn limit and time taken to light for standard ignition and laser ignition is presented.

1. Introduction

Conventional spark ignition (SI) using high energy electrical igniters is near its limit of durability and flexibility for its use in the ignition of lean air/fuel mixtures in stationary gas turbine applications. Laser ignition (LI) offers the potential to consistently ignite lean air/fuel mixtures with reduced combustion times whilst also addressing the durability issues associated with conventional SI systems [1–3]. Potential for the use of leaner air/fuel mixtures is particularly attractive as this results in lower flame temperatures, reduced NO_x emissions and reduced CO emissions by providing an excess of O_2 for oxidation to CO_2.

The potential for the application of lasers in the ignition process was first identified shortly after the advent of pulsed laser sources in 1964 by Ramsden et al. [4] who demonstrated the breakdown of air using a focussed ruby laser. However, it was many years before any significant interest in LI developed, primarily due to the availability of suitable pulsed laser systems. Since then, extensive research into the application of lasers in the ignition of various systems such as internal combustion engines and natural gas reciprocating engines has been conducted [5,6].

The LI process typically involves the use of highly focussed UV to near-IR laser radiation on locally ionize target molecules in a combustible mixture, leading to full-scale combustion. Through manipulation of process parameters and depending on the combustible mixture composition, either photo-dissociation or multiphoton ionization can be achieved. In a review paper published in 2005, Phuoc et al. [7] categorized various LI techniques into three distinct mechanisms: thermal ignition, photochemical ignition and multiphoton ionization. Primarily due to its relative independence regarding absorption characteristics of the combustible mixture, multiphoton ionization has emerged as the most commonly applied laser-based ignition mechanism [8,9]. In this mechanism, ionization occurs as a result of collision of multiple incident photons with target molecules. Whilst shorter wavelength photons may be sufficiently energetic so as to allow single photon ionization, longer wavelengths (that is, visible or IR) require multiple collisions to dissociate electrons. Once released, these electrons readily absorb more photons by the process of inverse bremsstrahlung, increasing their kinetic energy. Collision of these excited electrons with target molecules causes further ionization, leading to avalanche breakdown of the combustible mixture.

A vast majority of ignition applications requires combustion to be initiated in multiple chambers (or ‘cans’) which possess a specific challenge regarding ignition window and the lean burn limit. For instance, in the case of the SGT-400 gas turbine which forms the basis of this investigation, there are six combustion cans which are lit consecutively using standard high energy igniters. During the ignition process, the air/fuel ratio in unlit

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cans becomes progressively leaner as successive cans light. This phenomenon, referred to as leaning out, is due to an increase in the flame loss coefficient which is induced as each can is lit, increasing the local air resistance in that can. This resistance diverts more of the compressors air through the remaining, unlit cans. If the starting air/fuel ratio was close to the lean burn limit, this leaning out may make ignition in these cans impossible. As such, in order to achieve reliable and repeatable combustion, the air/fuel ratio must be tailored so as to allow a sufficiently large ignition window, thus rendering air/fuel ratios approaching the lean burn limit unsuitable. It is therefore desired that the lean burn limit be increased or the time to light be reduced to such an extent that the cans light near simultaneously. Laser ignition has the potential to increase the lean burn limit and therefore allow the use of leaner combustible mixtures [10,11]. The use of a high repetition rate pulsed laser source, multiplexed to multiple cans, could also reduce the discrepancy regarding time taken to light for individual cans [12].

In this work, the lean burn limit (henceforth referred to as the lean air/fuel ratio) and time taken to light characteristics of laser ignition in a low pressure combustion test rig are investigated and compared with analogous results from the standard ignition using a high energy igniter. The effect of air mass flow rate is studied and the potential for lasers to overcome issues associated with combustion in multiple cans is discussed.

2. Experimental procedures

2.1. Low pressure combustion test rig

For this work, the atmospheric combustion facility (ACF) at the Siemens Firth Road site in Lincoln, UK was used as the experimental rig. The ACF can be fitted with a single combustor can from a range of Siemens industrial gas turbines. For the purpose of this investigation, the rig was fitted with a combustion can and pilot burner from an SGT-400 industrial gas turbine. Use of the ACF rig allowed the replication of starting conditions encountered in a full scale combustor can, that is, identical mass flow rates and inlet temperatures for both the fuel and air supplies.

In normal operation, combustion on the ACF rig was initiated using a high energy igniter. This igniter had a fixed repetition rate of two sparks per second. The spark was located at approximately 1.00 mm from the tip of the igniter, which was flush with the face of the burner.

2.2. Laser ignition system

A laser ignition system was developed utilizing a Q-switched Nd:YAG TEM_{00} laser (Brilliant; Quantel, Ltd.) with a pulse duration of 9 ns, operating at 10 Hz repetition rate and 1064 nm wavelength. The laser ignition system, along with the experimental set-up for the investigation, is shown in Fig. 1.

A polarization based optical attenuator was used to manipulate the laser power. This avoids unwanted thermal lensing effects associated with changing the flashlamp/Q-switch delay time to manipulate the output power, which can lead to changes in the spatial properties of the beam [13,14]. The polarization based variable attenuator consisted of a 1/2 wave plate and polarizing beam splitting cube, as shown in Fig. 1. A power meter (Maestro; Gentec Electro-Optics, Inc.) connected to a data acquisition and control computer was used to measure the power 'dumped' by this attenuator set-up and used to infer the value for power exiting the laser ignition system. A 1/4 wave plate was used to protect the laser source from back reflections, necessitating a beam dump at the unused face of the polarizing beam-splitting cube.

2.2.1. Laser igniter assembly

A custom laser igniter was designed as a like-for-like replacement for the existing standard igniter used with a SGT-400 pilot burner. The ignition lance consisted of a clear aperture for transmission of the laser beam, an a-spherical focussing optic with an effective focal length of 15.29 mm and an anti-reflective coated N-BK7 output window. The optical elements within the lance were spaced using copper washers. To ensure that no ingress of the combustible gaseous mixture within the combustion chamber occurred, the tip of the ignition lance was sealed with red silicone around the edge of the output window.

3. Results and discussion

The experimental work focused on: (i) calibration of the laser igniter to determine the required pulse energy to achieve the consistent spark formation at atmospheric pressure, (ii) determination of the lean air/fuel ratio at which successful ignition occurs for a given mass flow rate of air and (iii) monitoring the time taken to light the combustible mixture at each lean air/fuel ratio.

3.1. Calibration of the laser igniter

Initially, the laser pulse energy required for the spark formation was determined. Operating at 10 Hz repetition rate, the laser pulse

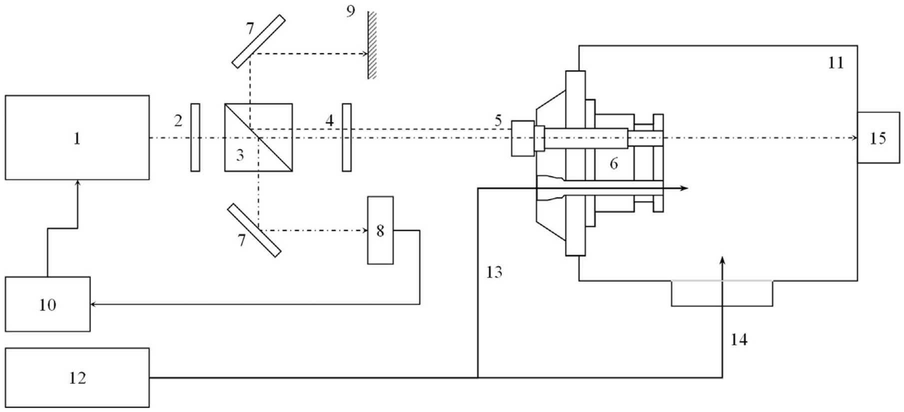

Fig. 1. Experimental set-up with (1) laser source, (2) 1/2 wave plate, (3) polarizing beam splitting cube, (4) 1/4 wave plate, (5) ignition lance, (6) SGT-400 pilot burner, (7) beam-steering mirror(s), (8) power meter, (9) beam dump, (10) data acquisition and control computer, (11) combustion chamber, (12) control panel, (13) gas in, (14) air in and (15) camera. The dashed-dot line represents the optical path whereas the dashed line represents the optical path for back reflections.