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Effect of flow velocity and temperature on ignition characteristics in laser ignition of natural gas and air mixtures

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ABSTRACT

Laser induced spark ignition offers the potential for greater reliability and consistency in ignition of lean air/fuel mixtures. This increased reliability is essential for the application of gas turbines as primary or secondary reserve energy sources in smart grid systems, enabling the integration of renewable energy sources whose output is prone to fluctuation over time. This work details a study into the effect of flow velocity and temperature on minimum ignition energies in laser-induced spark ignition in an atmospheric combustion test rig, representative of a sub 15 MW industrial gas turbine (Siemens Industrial Turbomachinery Ltd., Lincoln, UK). Determination of minimum ignition energies required for a range of temperatures and flow velocities is essential for establishing an operating window in which laser-induced spark ignition can operate under realistic, engine-like start conditions. Ignition of a natural gas and air mixture at atmospheric pressure was conducted using a laser ignition system utilizing a Q-switched Nd:YAG laser source operating at 532 nm wavelength and 4 ns pulse length. Analysis of the influence of flow velocity and temperature on ignition characteristics is presented in terms of required photon flux density, a useful parameter to consider during the development laser ignition systems.

1. Introduction

Laser ignition (LI) of air/fuel mixtures in gas turbines offers many potential advantages over conventional high energy spark ignition (SI) systems. Chief amongst these advantages is the potential for consistent and reliable ignition of leaner air/fuel mixtures, essential for the application of gas turbines as primary or secondary reserve energy sources in smart grid systems as frequent start-ups are a requirement. Additionally, LI systems have been shown to address the durability issues associated with conventional SI systems during engine operation [1–3].

Extensive research into the application LI for various applications such as internal combustion engines and natural gas reciprocating engines has been conducted [4,5]. 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., who demonstrated breakdown of air using a focussed ruby laser [6]. The LI process typically involves the use of tightly focussed UV to near-IR laser radiation to locally ionize target molecules in a combustible mixture, leading to full-scale combustion. Through manipulation of process parameters and depending on combustible mixture composition, either photo-dissociation or multi-photon ionization can be achieved. In a review paper published in 2005, Phuoc et al. categorized various LI techniques into three distinct mechanisms; thermal ignition, photochemical ignition and multiphoton ionization [7]. Due primarily 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 for 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.

The ability to manipulate the location of the laser spark, and therefore the ignition kernel, has long been heralded as a key advantage of LI over conventional SI. This is because, under engine-like conditions, optimal position of the laser spark is dependent on local flow velocity and equivalence ratio, both of which are influenced by numerous factors such as air/fuel mass flow rates and chamber geometry. LI systems can be utilized as an effective means of determining suitability of operating conditions for a given spark location. This was highlighted in a study by Barbosa et al. in which LI of C_3H_8/air mixtures using a Q-switched Nd:YAG was compared with conventional SI of the same mixture

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in an experimental combustion test rig [10]. It was found that the ignition time was reduced in the case of LI relative to SI, with this attributed to the ignition location being better optimized in the case of the former. The use of lasers for determining the minimum ignition energy, E_{min}, of combustible mixtures was first investigated by Weinberg et al., who studied the LI of CH_4/air with varying pressure using a Q-switched Ruby laser [11]. Phuoc also investigated the LI of CH_4/air mixtures, identifying an increase in E_{min} towards both the lean and rich side of stoichiometry [12]. Beduneau investigated the effect of flow velocity on the E_{min} of CH_4/air mixtures during LI using high speed Schlieren imaging [13]. It was found that, with increasing flow velocity, E_{min} increased on both the rich side and the lean of the equivalence ratio. Mullet et al. investigated the effect of beam mode (that is, intensity distribution) and focal length on the E_{min} required for successful ignition in an internal combustion engine using a Q-switched Nd:YAG operating at 1064 nm with a pulse length of 10 ns [14]. It was found that the E_{min} increased with increasing focal length, as the ability to tightly focus the beam was reduced and the Rayliegh range increased. Relative to focal properties, the effect of beam mode on E_{min} was found to be negligible.

In this work, the effect of temperature and flow velocity on E_{min} between the upper and lower flammability limits for a natural gas and air mixture are investigated, representative of realistic engine-like start conditions in different environments. The magnitude of influence that temperature and flow velocity have on the minimum photon flux density required for successful initiation of combustion is studied and 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.

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 4 ns, operating at 10 Hz repetition rate and 532 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 [14,15]. The polarization based variable attenuator consisted of a ½ 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 ¼ 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 the SGT-400 pilot burner. The laser igniter consisted of a clear aperture for transmission of the laser beam, and 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, as shown in Fig. 2. The laser-induced spark was located approximately 1 cm from the face of the burner. 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.

The laser pulse energy required for spark formation in air under atmospheric conditions was determined. Operating at 10 Hz repetition rate, the laser pulse energy was gradually increased until consistent sparking was observed. A photodiode sensor (VTB1012H; Excelitas Technologies Corp.) with a peak response of 920 nm and a spectral response of 320 to 1100 nm, and an oscilloscope (DSOX2002A; Agilent, Incs.) operating at 70 MHz and 2 GS/s were connected to a data acquisition computer and used to record the number of sparks formed over a period of 50 seconds, corresponding to a maximum of 500 sparks. The power was monitored over the duration of this measurement and averaged. At incident pulse energies of less than 3.69 mJ no spark formation occurred, with inconsistent spark formation observed for incident pulse energies between 3.69 and 6.12 mJ. Consistent spark formation was found to occur for incident pulse energies above 6.12 mJ.

3. Results and discussion

The experimental work focused on (i) determination of minimum ignition energies (E_{min}) between the upper and lower flammability limits for a natural gas and air mixture and (ii) determination of the effect of flow velocity and temperature on E_{min}.

3.1. Determination of minimum ignition energy

The minimum ignition energies between the upper and lower flammability limits for a natural gas and air mixture were determined using a half-interval search algorithm, accurate to within the minimum resolution of the polarization based variable attenuator. This process was repeated for each data point to ensure accuracy.

Initially, the flow velocity in the swirler (v_{sw}, henceforth referred to as flow velocity) was kept constant at 38 m/s. The flow velocity was a function of air mass flow rate, inlet temperature and pressure and was attained by keeping the air mass flow rate and inlet temperature constant at 230 g/s and 338.15 K, respectively. The air/fuel ratio was manipulated by varying the gas flow rate between 0.42 g/s and 1 g/s. The flow velocity and temperature were chosen on the basis of their being representative of typical starting conditions for a sub 15 MW industrial gas turbine.

Allowing time for the mass flow rate of the gas to settle and the combustible mixture to reach equilibrium at a predetermined air/fuel ratio, the laser igniter was activated for a period of five seconds, corresponding to fifty laser pulses. During this time, the camera feed was monitored for successful ignition.

The E_{min} for a given air/fuel ratio was determined, with E_{min} defined as the threshold pulse energy below which failure to ignite the mixture within the five second time period occurred. The minimum ignition energies between the upper and lower flammability limits for a natural gas and air mixture are shown in Fig. 3.