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

J. Griffiths (a), M.J.W. Riley (b), A. Borman (a), C. Dowding (a), A. Kirk (b), R. Bickerton (a)

a Laser and Photonics Engineering Group, School of Engineering, University of Lincoln, Brayford Pool, Lincoln, LN6 7TS, United Kingdom

b Combustion Group, School of Engineering, University of Lincoln, Brayford Pool, Lincoln, LN6 7TS, United Kingdom

Received 10 June 2014, Revised 13 August 2014, Accepted 8 September 2014, Available online 26 September 2014

doi:10.1016/j.optlaseng.2014.09.002

Highlights

- Laser ignition of natural gas and air conducted in an atmospheric pressure combustion test rig.
- Minimum ignition energy for a natural gas–air mixture under engine like conditions investigated.
- Analysis of influence of flow velocity and temperature on ignition characteristics conducted.
- Required threshold photon flux density for ignition of a natural gas–air mixture determined.

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.

Keywords

Laser ignition;

Gas turbine;

Minimum ignition energy;

Air/fuel ratio

---

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], [2] and [3].

Extensive research into the application LI for various applications such as internal combustion engines and natural gas reciprocating engines has been conducted [4] and [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] and [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 C3H8/air mixtures using a Q-switched Nd:YAG was compared with conventional SI of the same mixture 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, Emin, of combustible mixtures was first investigated by Weinberg et al., who studied the LI of CH4/air with varying pressure using a Q-switched Ruby laser [11]. Phuoc also investigated the LI of CH4/air mixtures, identifying an increase in Emin towards both the lean and rich side of stoichiometry [12]. Beduneau investigated the effect of flow velocity on the Emin of CH4/air mixtures during LI using high speed Schlieren imaging [13]. It was found that, with increasing flow velocity, Emin 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 Emin 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 Emin 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 Emin was found to be negligible.

In this work, the effect of temperature and flow velocity on Emin 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 TEM00 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.

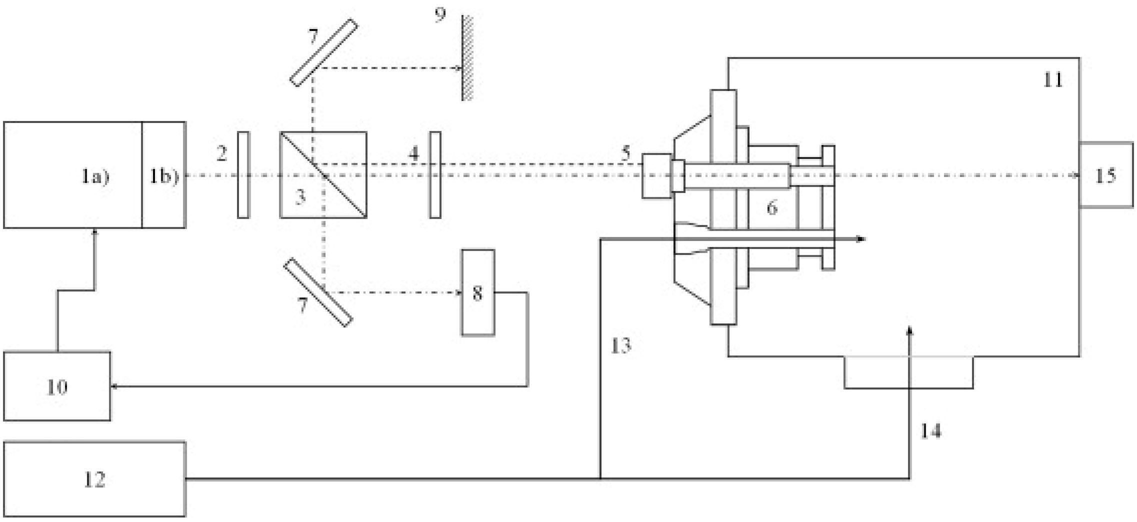

Fig. 1.

Experimental set-up with (1a) laser source, (1b) SHG module, (2) ½ wave plate, (3) polarizing beam splitting cube, (4) ¼ 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.

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] and [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.

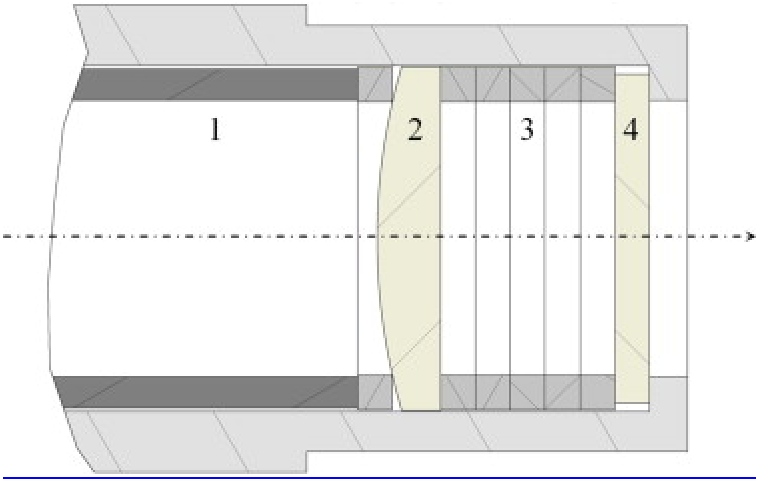

Fig. 2.

Schematic diagram of laser igniter assembly tip with (1) locking screw, (2) a-spherical focussing optic, (3) copper washers and (4) anti-reflective coated N-BK7 output window. The dashed-dot line represents the optical path.

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 (Emin) 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 Emin.

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 (vsw, 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 Emin for a given air/fuel ratio was determined, with Emin 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.

Fig. 3.

Minimum ignition energy for a natural gas and air mixture against air/fuel ratio (532 nm, 10 Hz, 38 m/s flow velocity, 338.15 K).

Fig. 3 reveals that mixtures with air/fuel ratios of less than 230 or more than 548 failed to ignite, with a minimum pulse energy at which combustion was successfully initiated of 13 mJ. The air/fuel ratio at which the lean burn limit is reached of 548 is comparable to that of approximately 580 reported previously for laser ignition of a natural gas and air mixture using the same atmospheric combustion test rig [3]. This relative reduction in lean burn limit can be attributed to an increase in flow velocity as a result of increased air inlet temperature. The effect of flow velocity on Emin is discussed in Section 3.1.2.

It should be noted that, under realistic engine-like conditions, the air/fuel ratio in the vicinity of the ignition location may vary significantly from that reported for the swirler. As such, the experimentally determined flammability limits in Fig. 3 were compared with lean flammability limit (LFL) and upper flammability limit (UFL) data for natural gas and air mixtures from literature; 5% and 15.6% of natural gas by volume respectively [16]. It can be observed that the experimentally determined flammability limits correspond to an LFL and UFL of 0.32% and 0.76% of natural gas by volume respectively, approximately 20 times leaner than values obtained from literature. This suggests that the air/fuel ratio is significantly richer in the vicinity of the laser spark.

The following subsections present Emin for two additional flow velocities (48 m/s and 51 m/s) and temperatures (378.15 K and 418.15 K).

3.1.1. Effect of flow velocity

The effect of flow velocity on Emin was investigated by increasing the mass flow rate of air into the chamber whilst keeping the chamber temperature constant at 338.15 K. The minimum ignition energy with varying air/fuel ratio at flow velocities of 45 m/s and 51 m/s is shown in Fig. 4 and Fig. 5 respectively.

Fig. 4.

Minimum ignition energy for a natural gas and air mixture against air/fuel ratio (532 nm, 10 Hz, 45 m/s flow velocity, 338.15 K).

Alongside Fig. 3, Fig. 4 and Fig. 5 reveal an increase in Emin as the flow velocity is increased. It should be noted that the observed increase in Emin with increasing flow velocity as the mixture becomes leaner is not consistent with observations made by Beduneau [13]. However, the increase in Emin for both rich and lean mixtures with increasing flow velocity can be rationalized in terms of increased convection losses, requiring more energy to successfully initiate a combustion event. During the initiation stage of combustion, the heat release rate of the chemical reaction must balance the rate of heat loss; therefore, high flow velocities necessitate the use of greater pulse energies to create a volume of gas in which the rate of heat generation is sufficient to compensate for convective heat losses.

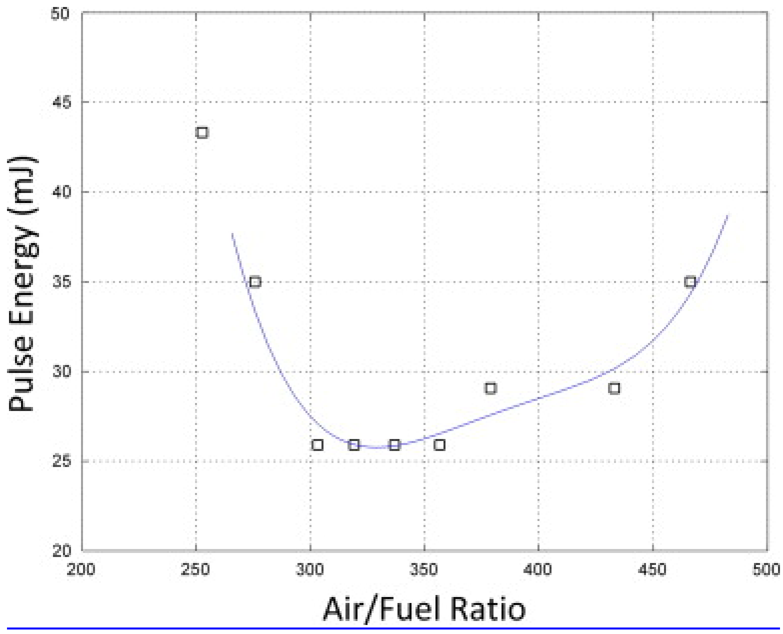

Fig. 5.

Minimum ignition energy for a natural gas and air mixture against air/fuel ratio (532 nm, 10 Hz, 51 m/s flow velocity, 338.15 K).

Another critical consideration in the case of increasing flow velocity is quenching distance. For a flame kernel to grow and propagate into a self sustaining flame, its minimum dimension must exceed the quenching distance, with the minimum quenching distance increasing in proportion to the intensity of turbulence. Theoretical and experimental work has shown that the minimum energy necessary to heat (to its adiabatic flame temperature) a volume of gas equal to the minimum quenching distance is proportional to the cube of the quenching distance [17]. As such, an increase in the turbulent flow requires an exponential increase in the ignition energy to initiate successful combustion of the air/fuel mixture.

3.1.2. Effect of temperature

The effect of chamber temperature on Emin was investigated by preheating the air in the combustion chamber whilst keeping the flow velocity constant at 38 m/s. The minimum ignition energy with varying air/fuel ratio at temperatures of 378 K and 418.15 K is shown in Fig. 6 and Fig. 7 respectively.

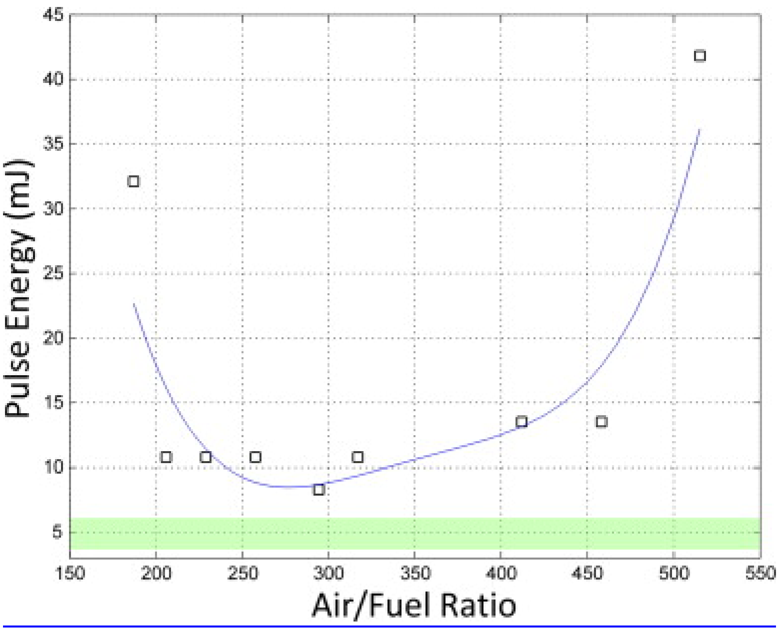

Fig. 6.

Minimum ignition energy for a natural gas and air mixture against air/fuel ratio (532 nm, 10 Hz, 38 m/s flow velocity, 378.15 K). The gray band represents the pulse energy range over which inconsistent spark formation occurred.

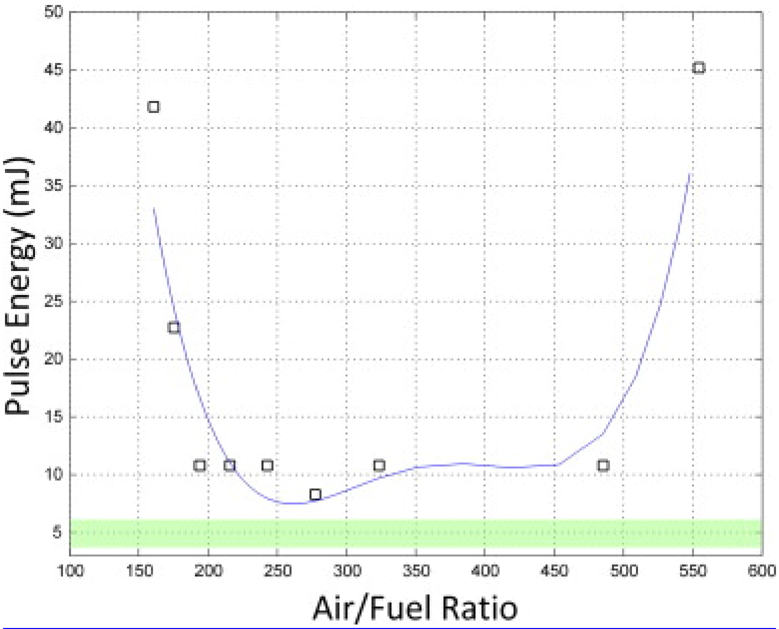

Fig. 7.

Minimum ignition energy for a natural gas and air mixture against air/fuel ratio (532 nm, 10 Hz, 38 m/s flow velocity, 418.15 K). The gray band represents the pulse energy range over which inconsistent spark formation occurred.

Figs. 6 Fig. 6 and Fig. 7 reveal a 'bottoming-out' occurring at incident pulse energies greater than the threshold for consistent spark formation under atmospheric conditions for the current optical set-up. This was attributed to the increased flow velocity in the location of the laser spark within the combustion chamber relative to the atmospheric conditions in which the threshold for consistent spark formation was determined. Specific to the multiphoton ionization laser ignition process, high flow velocities may have the effect of removing electrons generated by the leading edge of the laser pulse from the focal point of the beam before further collision can occur, effectively reducing the duration and density of the laser induced plasma [7].

3.2. Influence of flow velocity and temperature on ignition characteristics

Whilst commonly reported in literature, the minimum ignition energy can be misleading as it neglects laser parameters such as focal properties, wavelength and pulse duration. The photon flux density quantifies the number of photons per unit time per unit area and is particularly useful as it incorporates key laser parameters relevant to the generation of laser-induced plasmas in practical applications such as ignition. In order to calculate the photon flux density we require the maximum occurring optical power, Pp, and minimum waist at focus, w0. Firstly we assume a Gaussian temporal pulse shape, as defined using the following equation [12]:

equation(1)

$E_{p(\tau)} = E_0 e^{-\tau^2/\tau_0^2}$<img height="18" border="0" style="vertical-align:bottom" width="92" alt="View the MathML source" title="View the MathML source" src="http://origin-ars.els-cdn.com/content/image/1-s2.0-S0143816614002218-si0001.gif">Ep(τ)=E0e−τ2/τ02

where Ep is the laser pulse energy, E0 is the maximum laser pulse energy and τ is time. If we consider the full width at half maximum (FWHM) of this Gaussian pulse to be equal to the pulse duration, τFWHM, the time at which the pulse energy is at its maximum, τ0, can be found by

equation(2)

$\tau_0 = \frac{\tau_{FWHM}}{2\sqrt{\ln 2}}$<img height="27" border="0" style="vertical-align:bottom" width="71" alt="View the MathML source" title="View the MathML source" src="http://origin-ars.els-cdn.com/content/image/1-s2.0-S0143816614002218-si0002.gif">τ0=τFWHM2ln2

The maximum occurring optical power during the Gaussian pulse is calculated using Eq. (3).

equation(3)

$P_p = \frac{E_P}{\tau_0\sqrt{\pi}}$<img height="31" border="0" style="vertical-align:bottom" width="62" alt="View the MathML source" title="View the MathML source" src="http://origin-ars.els-cdn.com/content/image/1-s2.0-S0143816614002218-si0003.gif">Pp=EPτ0π

The minimum waist of the laser beam is given as

equation(4)

$w_0 = \left(\frac{2\lambda}{\pi}\right)\left(\frac{f}{d_L}\right)$<img height="33" border="0" style="vertical-align:bottom" width="97" alt="View the MathML source" title="View the MathML source" src="http://origin-ars.els-cdn.com/content/image/1-s2.0-S0143816614002218-si0004.gif">w0=(2λπ)(fdL)

where f is the effective focal length of the lens, dL is the beam diameter incident on the focussing optic and λ is the wavelength. The photon flux density (photons/cm2 s) is calculated using

equation(5)

$F_{ph} = \frac{P_p\lambda}{\pi\omega_0^2hc}$<img height="34" border="0" style="vertical-align:bottom" width="72" alt="View the MathML source" title="View the MathML source" src="http://origin-ars.els-cdn.com/content/image/1-s2.0-S0143816614002218-si0005.gif">Fph=Ppλπω02hc

where h is Plank's constant and c is the speed of light. Table 1 summarizes the findings of this investigation, presenting the minimum value of Emin between the flammability limits, Emin', the coefficient of variation and the difference in magnitude for Emin between the flammability limits, Dmax–min with varying flow velocity and temperature. Also presented is the minimum ignition photon flux density, Fph', corresponding to the minimum value of Emin between the flammability limits.

Table 1.

Emin', Dmax–min, co-efficient of variation and Fph' with varying flow velocity and temperature (532 nm, 10 Hz).

T (K)	vsw (m/s)	Emin' (mJ)	Dmax–min (mJ)	Coefficient of variation	Fph' (photons/cm2 s)
338.15	38	13.52	21.47	0.38	1.62×1032
338.15	45	22.70	22.46	0.26	2.71×1032
338.15	51	25.90	17.41	0.20	3.09×1032
378.15	38	8.3	33.50	0.69	9.92×1031
418.15	38	8.3	36.86	0.76	9.92×1031

Increasing flow velocity results in a reduction in the size of the flammability range, as revealed in the observed decrease in Dmax–min and coefficient of variation. The opposite is true in the case of increasing temperature, with the flammability window widening.

Srivastava et al. reported minimum photon flux values in the order of between 7.5×1029 and 1.5×1031 photons/cm2 s for laser ignition of natural gas and air, lower than those observed in this investigation [18] and [19]. This discrepancy in photon flux densities can be attributed to the elevated pressure of 10 bar at which Srivastava et al. determined these values, with minimum ignition energy exhibiting an inverse square relationship with pressure [20].

4. Conclusions

The effect of temperature and flow velocity on minimum ignition energy between the upper and lower flammability limits for a natural gas and air mixture under realistic, engine-like conditions have been investigated. 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.

For the first time, the effect of flow velocity and temperature on gas turbine ignition characteristics under realistic engine-like conditions has been investigated. Initially the threshold pulse energy required for laser induced spark formation was determined and found to be 3.69 mJ, with consistent spark formation occurring at pulse energies greater than 6.12 mJ.

The influence of flow velocity and temperature on the minimum ignition energies between the upper and lower flammability limits were determined. It was found that the flammability range reduced as the flow velocity was increased from 38 m/s to 51 m/s at a constant temperature of 338.15 K. This was attributed to increased convective heat losses and characterized by a 48% decrease in the coefficient of variation for minimum ignition energy. Conversely, the flammability window was found to widen as the temperature was increased from 338.15 K to 418.15 K at a constant flow velocity of 38 m/s, indicated by a doubling in the coefficient of variation for minimum ignition energy.

Photon flux density has been identified as a particularly useful parameter for characterization of minimum ignition energy, incorporating key laser parameters relevant to the multiphoton laser ignition process. Experimental observations suggest that photon flux densities in the order of 1032 photons/cm2 s are required for ignition of natural gas and air mixtures, with these values found to be comparable with equivalent values from literature.

This work has demonstrated that the local air/fuel ratio in the vicinity of the ignition kernel can vary significantly from the stated air/fuel ratio under realistic engine-like conditions. Examination of the experimentally determined and theoretical flammability limits suggests that, in this instance, the air/fuel ratio is approximately 20 times richer in the vicinity of the laser spark. This work has identified flow velocity and temperature in the vicinity of the laser induced spark as key factors influencing successful initiation of combustion during the multiphoton laser ignition process under gas dynamic conditions representative of real engine operation. The effect of flow speed and temperature on the multiphoton laser ignition process remains an active research field.

Acknowledgments

The authors would like to thank Siemens Industrial Turbomachinery Ltd. (SITL) for funding this investigation as part of a wider investigation into laser ignition for gas turbines.

References

[1]

Herdin G, Klausner J, Wintner E, Weinrotter M, Graf J, Iskra K. Laser ignition: a new concept to use and increase the potentials of gas engines. In: Proceedings of the ASME internal combustion engine division 2005 fall technical conference; 2005.

[2]

J. Griffiths, J. Lawrence, P. Fitzsimons

Effect of igniton location on the in-process removal of combustion deposits from the output window of a gas turbine laser ignition system

Opt Laser Technol, 48 (2013), pp. 326–330

[3]

J. Griffiths, M. Riley, A. Kirk, A. Borman, J. Lawrence, C. Dowding

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

Opt Lasers Eng, 55 (0) (2014), pp. 262–266

[4]

Dale J, Smy P., Clements R. Laser ignited internal combustion engine—an experimental study; 1978.

[5]

Bihari B, Gupta SB, Sekar RR, Gingrich J, Smith J. Development of advanced laser ignition system for stationary natural gas reciprocating engines. In: ARES-ARICE symposium on gas fired reciprocating engines; 2005. pp. 601–8.

[6]

S.A. Ramsden, W.E. Davies

Radiation scattered from the plasma produced by a focused ruby laser beam

Phys Rev Lett, 13 (7) (1964), p. 227

[7]

X.P. Tran

Laser-induced spark ignition fundamental and applications

Opt Lasers Eng, 44 (5) (2006), pp. 351–397

[8]

P.D. Ronney

Laser versus conventional ignition of flames

Opt Eng, 33 (1994), p. 510

[9]

H. Kopecek, H. Maier, G. Reider, F. Winter, E. Wintner

Laser ignition of methane–air mixtures at high pressures

Exp Therm Fluid Sci, 27 (4) (2003), pp. 499–503

[10]

Comparisons between spark plug and laser ignition in a gas turbine combustor. In: Proceedings of the European combustion meeting; 11–13 April 2007.

[11]

F. Weinberg, J. Wilson

A preliminary investigation of the use of focused laser beams for minimum ignition energy studies

Proc R Soc Lond Ser A Math Phys Sci, 321 (1544) (1971), pp. 41–52

[12]

T.X. Phuoc, F.P. White

Laser-induced spark ignition of CH4/air mixtures

Combust Flame, 119 (3) (1999), pp. 203–216

[13]

J. Beduneau, B. Kim, L. Zimmer, Y. Ikeda

Measurements of minimum ignition energy in premixed laminar methane/air flow by using laser induced spark

Combust Flame, 132 (4) (2003), pp. 653–665

[14]

J. Mullett, R. Dodd, C. Williams, G. Triantos, G. Dearden, A. Shenton, et al.

The influence of beam energy, mode and focal length on the control of laser ignition in an internal combustion engine

J Phys D, 40 (15) (2007), p. 4730

[15]

Y.- Chen, J.W.L. Lewis, C. Parigger

Spatial and temporal profiles of pulsed laser-induced air plasma emissions

J Quant Spectrosc Radiat Transf, 67 (2) (2000), pp. 91–103

[16]

S.Y. Liao, Q. Cheng, D.M. Jiang, J. Gao

Experimental study of flammability limits of natural gas–air mixture

J Hazard Mater, 119 (1–3) (2005), pp. 81–84

[17]

A.H. Lefebvre

Gas turbine combustion

(2nd ed)Taylor & Francis Group, New York, NY (1999)

[18]

D.K. Srivastava, K. Dharamshi, A.K. Agarwal

Flame kernel characterization of laser ignition of natural gas–air mixture in a constant volume combustion chamber

Opt Lasers Eng, 49 (9–10) (2011), pp. 1201–1209

[19]

D.K. Srivastava, E. Wintner, A.K. Agarwal

Effect of focal size on the laser ignition of compressed natural gas–air mixture

Opt Lasers Eng, 58 (0) (2014), pp. 67–79

[20]

M.V. Blanc, P.G. Guest, Elbe Gv, B. Lewis

Ignition of explosive gas mixtures by electric sparks: III. Minimum ignition energies and quenching distances of mixtures of hydrocarbons and ether with oxygen and inert gases

Symp Combust Flame Explos Phenom, 3 (1) (1948), pp. 363–367