Combustion and Flame 167 (2016) 164–171

Contents lists available at ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

The effect of humidity on hydroxyl and ozone production by nanosecond discharges

Daniel Singleton[a,1,*], Campbell Carter[b], Scott J. Pendleton[a,2], Christopher Brophy[c], Jose Sinibaldi[c,3], John W. Luginsland[d,4], Michael Brown[b], Emanuel Stockman[e], Martin A. Gundersen[a]

[a] University of Southern California, Los Angeles, CA 90089, USA
[b] Air Force Research Laboratory, Wright-Patterson Air Force Base, OH 45433 USA
[c] Naval Postgraduate School, Monterey, CA 93943, USA
[d] NumerEx, Ithaca, NY 14850, USA
[e] Princeton University, Princeton, NJ 08544, USA

ARTICLE INFO

Article history:
Received 19 October 2015
Revised 19 February 2016
Accepted 19 February 2016
Available online 14 March 2016

Keywords:
Non-equilibrium plasma
Nanosecond pulsed power
Transient plasma ignition
Planar laser induced florescence
Hydroxyl
Ozone

ABSTRACT

The interplay of humidity and non-equilibrium, transient plasma was studied via ignition experiments in a C_2H_4–air mixture, concentration measurements in humid air, and detailed simulations. Hydroxyl (OH) and ozone (O_3) produced via non-equilibrium plasma were characterized in a flowing H_2O–air mixture at atmospheric pressure with varying the levels of humidity using planar laser-induced fluorescence (PLIF) and UV absorption, respectively. The OH, which was created in the discharge streamers, peaked at a concentration of $\sim 5 \times 10^{14}$/cm^3 and then decayed below 1×10^{14}/cm^3 after $\sim$100 μs. O_3, which is long lived, peaked at a concentration of 1.4×10^{15}/cm^3. An increase in humidity from $X_{H_2O} \approx 0.2\%$ to 1% resulted in a monotonic increase in the concentration of OH and a 67% decrease in that of O_3. Zero-dimensional Boltzmann modeling of non-equilibrium plasma discharges in humid air showed qualitative agreement with these results and points to the decrease in O concentration (with increasing humidity) as the reason for the decreased O_3 concentration. In spite the dramatic decline in X_{O_3} with increased humidity, there was no strong commensurate effect on ignition and flame propagation in C_2H_4–air mixtures: Peak pressure rise rate was at its maximum value at $X_{H_2O} = 1\%$ but was only 25% less at $X_{H_2O} = 5\%$.

1. Introduction

Transient plasma ignition (TPI) has several advantages over traditional spark ignition used in most combustion applications. TPI has consistently demonstrated reductions in ignition delay, especially under fuel-lean conditions, resulting in improved efficiency and reduced emissions from a variety of combustion engines [1–6]. TPI is different from traditional approaches to ignition in that the high-voltage pulse used to initiate ignition is less than 100 ns in duration, whereas in traditional approaches the high-voltage pulse may last from many μs to several ms. The short, fast-rise-time pulses prevent an arc from occurring and produce a non-equilibrium plasma, characterized by a high electron temperature, T_e, and a low gas temperature, T_g ($T_e \gg T_g$). In a non-equilibrium plasma, the ionization process is dominated by field-driven, energetic electrons colliding with non-excited atoms and molecules. Furthermore, the energy efficiency is high and significant energy goes into creating highly energetic electrons instead of heating the gas, and the geometry of the electrodes can be designed in such a way that (a) reactive species are produced throughout a volume and (b) multi-point ignition can occur [7]. The result is a more efficient and faster combustion process than with initiation by the traditional thermal spark [8].

Humidity is a variable in combustion environments that can arise from ambient conditions (where it is generally limited to concentrations of ~1% by volume) but also due to mixing of combustion products with fresh reactants (e.g. in an internal combustion engine with exhaust gas recirculation, in swirl combustors, and in

* Corresponding author at: Transient Plasma Systems, 1751 Torrance Blvd, Suite K, Torrance, CA 90501, USA.
E-mail address: dsinglet@usc.edu (D. Singleton).
[1] Present address: Transient Plasma Systems, Torrance, CA 90501, USA.
[2] Present address: Old Dominion University, Norfolk, VA 23529, USA.
[3] Present address: Lawrence Livermore National Laboratory, Livermore, CA 94550, USA.
[4] Present address: Air Force Office of Scientific Research, Arlington, VA 22203, USA.

http://dx.doi.org/10.1016/j.combustflame.2016.02.016
0010-2180/

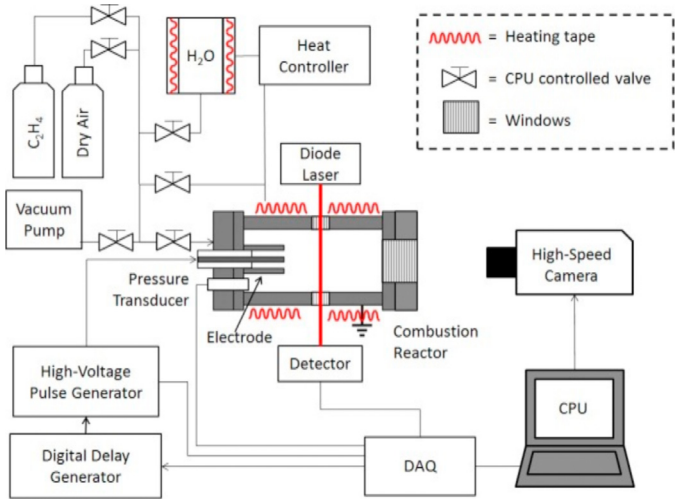

Fig. 1. Setup for ignition experiments using high-pressure heated chamber.

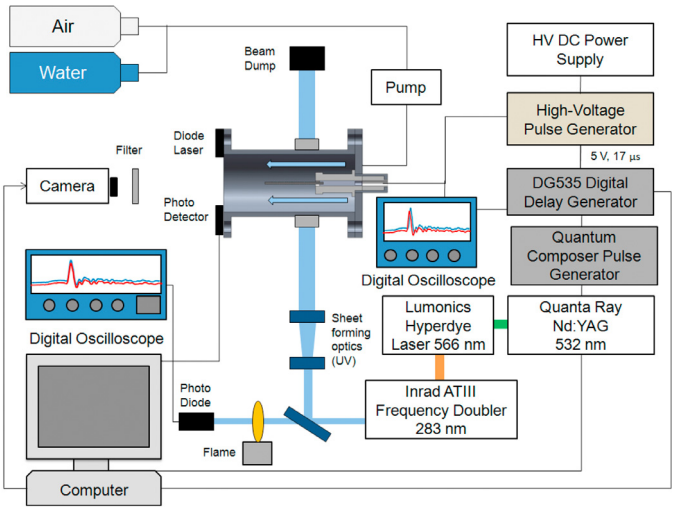

Fig. 3. Setup for OH-PLIF experiment.

afterburners). Its effect coupled with non-equilibrium plasma for ignition or flame propagation is unclear; therefore, the goal of this study was to determine the effect upon combustion. For this purpose, we employed a static chamber with mixtures of C_2H_4 and humid air and transient plasma for ignition (along with a comparison of ignition with a standard spark igniter). These measurements were complimented with diagnostic measurements—to characterize both OH and O_3 concentrations—of humid air activated with transient plasma and with simplified numerical simulation of the transient plasma in humid air.

2. Experiments

2.1. Combustion measurements

A static combustion chamber (ID of 10.2 cm and a length of 20.3 cm) was used with varying levels of humidity. The ignition experiment was performed at 2 atm and 473 K with pre-mixed, lean ($\phi = 0.8$) ethylene–air (C_2H_4–air). A diagram of the experimental setup is shown in Fig. 1. Pressure measurements were used to characterize the ignition process. Water was added to the air by bubbling it through a water bath. The concentration was measured using tunable diode laser absorption spectroscopy (TDLAS, see below for more details); here, the diode-laser beams were directed through the sapphire windows, as shown in Fig. 1. The electrode used for this experiment was an NGK R0045J-11 spark plug that had a non-resistive core and uniform gap; the electrode was located in the center of one flange of the cylindrical chamber. A 12-ns, 40-kV, 50-mJ pulse [6] was used to produce transient plasma and initiate combustion in the quiescent mixture. Each condition was repeated a minimum of 5 times, and the results are shown in Fig. 2. Both the *time to peak pressure* (t_{peak}) and the *peak pressure rise rate*, $(dP/dt)_{peak}$, improved as the humidity was increased to $X_{H_2O} = 1\%$; thereafter, the combustion performance decreased (i.e., longer t_{peak} and lower $(dP/dt)_{peak}$ values were observed): at $X_{H_2O} = 5\%$, $(dP/dt)_{peak}$ was about 25% below the value found at $X_{H_2O} = 1\%$, but this value of $(dP/dt)_{peak}$ was only slightly less than that at $X_{H_2O} = 0.5\%$. For comparison, the same conditions were examined using traditional spark ignition with a 15-µs, 15-kV, 100-mJ pulse, where a change in X_{H_2O} in the same range resulted in negligible differences in t_{peak} and $(dP/dt)_{peak}$, as shown in Fig. 2a; interestingly, the curve for TPI at $X_{H_2O} = 3\%$, is nearly coincident with the two curves for spark ignition.

2.2. Diagnostic measurements

To characterize the humid air activated with the plasma, the same chamber was used (Fig. 3). However, for this part of the study the chamber was mounted vertically, the end wall (normally occupied by the windows) was removed, and a constant flow of humid air (made uniform with glass beads placed in the bottom of the chamber) was directed through the chamber (see Fig. 4). The

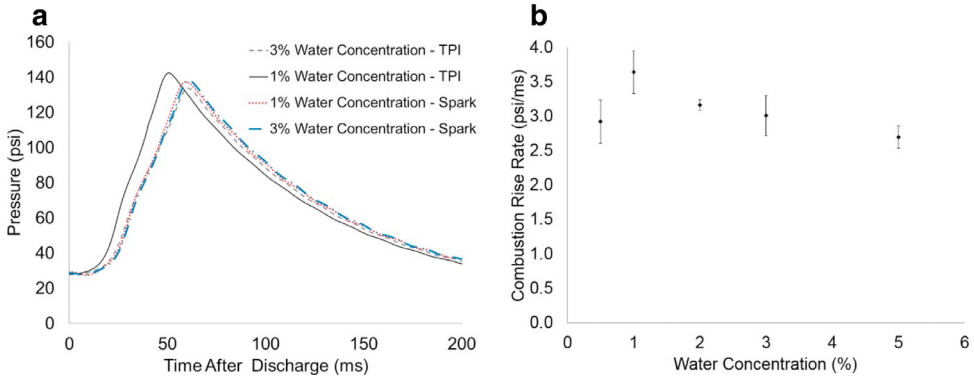

Fig. 2. Results from the ignition and combustion of C_2H_4–air ($\phi = 0.8$) after a 12-ns, 40-kV, 50-mJ discharge. (a) Comparison of combustion pressure rise between ignition for $X_{H_2O} = 3\%$ and 1%. (b) Comparison of combustion pressure rise rate with X_{H_2O} varying from 0.5% to 5%. Error bars represent the standard deviation of the measurement set.