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Post discharge evolution of a spark igniter kernel

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ABSTRACT

In many practical combustion devices, short duration, high-energy spark kernels are used to ignite combustible gases in turbulent flows. Here we examine the development of a high energy (~0.25 J) spark kernel created by a short duration (<1 μs) breakdown discharge across two opposed electrodes situated in a uniform air flow. Measurements of electrical energy supplied to the electrodes compare well to thermal energy deposited in the flow with deposition efficiencies exceeding 90%. These spark energies are used as inputs to a numerical model that simplifies the computations by replacing the complex, finite duration, energy deposition process with an instantaneously created, uniform kernel. The evolution of the kernel shape and size predicted by the computational model agrees well with experimental data obtained from high-speed schlieren images, including development of an asymmetry of the kernel between its upstream and downstream regions at later times. The predicted kernel evolution is shown to be essentially independent of the initial size and the composition of the kernel for a fixed deposition energy. The numerical results also reveal the importance of rapid entrainment of ambient air into the central region of the kernel, which quickly reduces the maximum temperatures in the kernel. In addition, the predicted O atom concentrations are well above equilibrium values, especially in the lower temperature regions of the kernel. The higher temperatures and O mole fractions found in the leading portion of the kernel are expected to be an important contributor to ignition in non-premixed combustion flows.

1. Introduction

Most practical combustion devices rely on some form of forced ignition to initiate the combustion process. The most common approach to forced ignition is an electric discharge [1], which typically results in the creation of a high energy spark kernel. Challenges associated with spark ignition are mainly due to operational constraints. For example, regulations limiting emissions and industrial standards requiring high efficiencies have driven a trend toward lean combustion, resulting in less reactive mixtures that are, therefore, more difficult to ignite [2,3]. Other challenging constraints on ignition include high altitude relight [4], high performance operation [5], and safety concerns [6]. Meeting these challenges necessitates improvements in our fundamental understanding of the spark ignition process [7].

Key developmental properties of the spark kernel depend on the energy and the duration over which energy deposition occurs. Much of the experimental work on spark ignition has been for low energy discharges [2,8] or long energy discharge durations [7,9], motivated by automotive applications. On the other hand, gas turbine combustors use a high energy (~1 J/pulse) igniter with capacitively coupled charge storage [10]. These systems discharge quickly (ns to μs), resulting in reduced thermal losses to the electrodes [8,11]. Similarly, high speed and high performance reciprocating engines have increasingly shifted to use short duration, high efficiency capacitive discharge ignition systems [12], to increase deposition efficiency and expand engine operating ranges.

Additionally, much of the previous experimental work has been performed under quiescent conditions [2,6,13,14]. However, the evolution of a spark kernel in many devices, including ground power gas turbines, aircraft engines, process air heaters and, to a lesser extent, automotive engines, occurs in a flowing environment. Likewise in many combustor environments where fuel and oxidizer are not premixed, or where there is significant non-uniformity in the local fuel–air ratio, the igniter location may experience non-flammable conditions [15]. Therefore, it is important to understand the evolution of a spark kernel created in a non-flammable region that must transit to a flammable region. Additionally, studying the development of a spark kernel in an air flow can also improve the understanding of ignition in premixed flows.

Computational models that can accurately predict the development of a spark kernel can provide information that is difficult to measure experimentally. For example, simulations can capture

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the non-equilibrium composition during the kernel evolution, including persistence of ionized species and radicals, which can greatly influence the ignition process [16–20]. Specifically, Kosarev et al. [21] highlighted the importance of O and H radicals on the chain reactions during ignition, and Takita et al. [22] investigated the effect of O, H, and N atoms on flame speed.

A number of efforts have focused on understanding the plasma physics associated with gas discharges [23]. These numerical approaches usually include the solution of the complex magneto-hydrodynamic equations governing the plasma development. Simplifications to spark kernel simulations have been performed that replace the complicated plasma modeling with a temporally distributed energy deposition process. For example, a number of premixed ignition studies exploring quiescent background conditions have employed numerical models where the deposited electrical energy was distributed within either a cylindrical or spherical volume in space [14,24–27], while the temporal energy deposition profile was specified or matched to experimental data.

Since the temporal energy deposition profile is not easy to measure for short duration discharges, it is desirable to employ a simpler initialization method for numerical simulations that requires only knowledge of the deposited spark energy. The deposited energy has been shown to be influential in the development of the kernel [28,29], and to the overall ignition probability [7]. Previous studies have employed various means to determine deposited spark energies, in both flowing systems [15,30,8] and bomb calorimeters [13,31,32]. For capacitive discharges, electrical energies can be calculated from $1/2CV^2$, which is typically greater than the deposited energy due to thermal energy losses in lines and electrodes. Here, C and V are capacitance and voltage, respectively. More accurate electrical energy measurements can be obtained by measurements of the current through and voltage across the electrodes. In bomb calorimeters, deposited energies have also been determined using pressure rise in a fixed volume. It has been suggested that deposition efficiencies, i.e., deposited thermal energy as a fraction of supplied electrical energy, should range from 30% for glow discharge, 50% for arc discharges, and up to 94% for breakdown discharge modes [11].

Most of the previous numerical studies of spark evolution in quiescent environments employed one- or two-dimensional simulations that assumed rotational symmetry. However, for spark kernel development in a flowing system, it is necessary to account for non-uniform mixing and convection that may be important to the ignition process. For example, the orientation of the electrodes with respect to the flow direction has been shown to effect the spark kernel [8]. This coupling with a flow has not been investigated and requires the inclusion of a 3D computational domain. In studies where the spark development has been validated against experimental measurements, a common measure of comparison has been growth in kernel size [26,33].

In order to address some of the deficiencies identified above, this paper focuses on characterizing the development of a spark kernel initiated in a crossflow of air. A computational model with a simplified initiation that represents short duration electrical discharges and accounts for ionized species is presented. Experimental measurements of kernel growth are used as a model validation database. The experimental data include precise energy measurements of the deposited spark energy.

2. Methods

2.1. Experimental setup

Measurements were acquired from a short duration, high energy spark discharge in an opposed electrode configuration, which is a common choice for ignition experiments [8,34]. The discharge was characterized by a combination of electrical measurements and a flow calorimeter to obtain the energy deposited into the gas. The subsequent evolution of the spark kernel was obtained from high speed schlieren and emission imaging. The details of the experiment are described below.

2.1.1. Spark discharge system and electrical measurements

The spark is generated in a gap between the ends of two co-linear cylindrical copper electrodes. The diameter of the copper electrodes, chosen to produce low impedance, is 3.18 mm, and the gap spacing is 6.4 mm to ensure a high breakdown voltage. The high energy, short duration discharge is created by a modified copper vapor laser (Metalaser 2051) capacitive power supply (see schematic in Fig. 1). The pulse rate of the supply is variable, and was set between 10 and 300 Hz in the current measurements. The voltage across the electrodes was measured close (~2 cm) to the gap using a high voltage probe (Tektronix P6015A). Current through the electrodes was measured 10 cm from the gap on the cathode side using a current monitor with a 5 ns response (Pearson model 6600).

Examples of measured current (I) and voltage (V) time traces are shown in Fig. 2. The results shown were obtained for the electrodes placed in a uniform, 8 m/s flow moving parallel to the electrode faces. From these measurements, the discharge lasts between 300 and 500 ns, depending on the metric used to define the duration. Also included in the figure is the evolution of the supplied electrical energy, as calculated from Eq. (1). Within 500 ns, essentially all of the approximately 0.25 J is supplied to the electrodes.

$$E_{supplied} = \int V(t)I(t)dt \quad (1)$$

2.1.2. Flow calorimeter and deposited energy measurements

In order to measure the fraction of supplied electrical energy deposited into the flow, a special calorimeter was developed. The

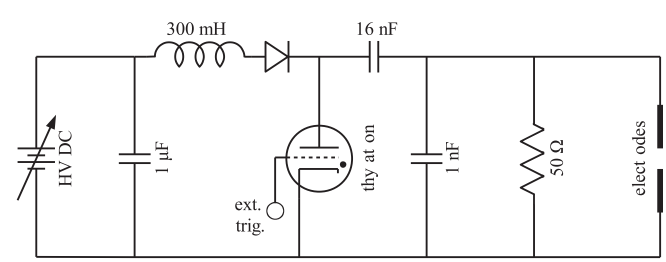

Fig. 1. Circuit diagram for electrode power supply.

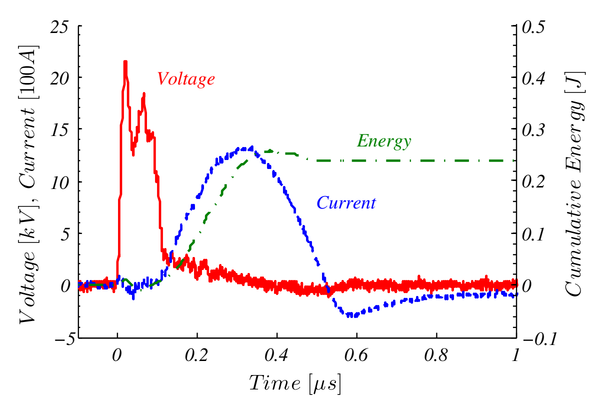

Fig. 2. Measured voltage (V) and current (I) time traces as well as integrated energy supplied (E).