High Energy Spark Kernel Evolution: Measurements and Modeling

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In many practical combustion devices, short duration, high-energy spark kernels are used to ignite combustible gases in high velocity, turbulent flows. Under these conditions, high energies are required to ensure reliable ignition. However, the majority of research in spark ignition has focused on lower energy sparks in low velocity or quiescent gases. Here we report on measurements obtained for 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. The same flow system geometry was studied with Large Eddy Simulations (LES). The initial spark energy, both supplied electrical energy and energy deposited into the flow, were measured and used to provide initial conditions for the LES. The time-resolved current and voltage supplied to the electrodes was obtained using fast response (∼5 ns) probes, and the deposited energy was measured with a specially designed flow calorimeter for a variety of flow velocities and turbulence intensities. The results reveal high deposition efficiencies (>90%) with negligible dependence on flow conditions. An analysis based on a full kinetic mechanism for ionized air shows that the spark generation process can be replaced by a simple uniform energy deposition assumption in the simulations. Based on LES studies using a range of initial conditions, the kernel evolution was found to be primarily sensitive to the amount of deposited energy. The kernel evolution, characterized with high speed schlieren and emission imaging, was used to validate the LES results. Initially, the kernel grows rapidly due to gas dynamic expansion, although the expansion is altered by the presence of the electrodes, resulting in air entrainment into the low pressure center of the kernel and the production of a toroidal-like structure within 100 µs after the electric discharge. This structure is observed in both the experimental and simulation data. In addition, both show that high temperatures exist longer in the downstream region of the kernel structure. The LES reveals that the more rapid temperature decay upstream is the result of enhanced entrainment and mixing of ambient air into the upstream region of the kernel. Thus it is likely the downstream edge of the toroidal kernel would be the dominant source of ignition.

1 Introduction

Ignition by an electric discharge, typically a spark, is a common approach for overcoming the initial activation energy barrier in a combustion system. This method is used in almost all automobile and aircraft engines because it is simple, compact, and reliable for extended periods of use. In a spark igniter, the electrons between the electrodes are accelerated by the applied electrical field [1], then the streamers generated at the anode propagate to the cathode [2, 3]. This forms a conductive channel, allowing the electrical power supply to deliver a high current through the channel. For premixed fuel-air mixtures, the electrical energy transferred into the gas initially causes the kernel to expand, but eventually flame chemistry drives the expansion [4–6]. The deposited energy
determines the initial condition of the kernel [7], yet the development continues as it is convected downstream. As the kernel moves, it grows due to mixing and thermal expansion [8–10]. Thus, the growth rate is related to the turbulence level around the kernel [9, 11] and the temperature inside the kernel [10]. The growth will affect the energy density of the kernel, which is a critical factor for successful ignition.

Furthermore in many practical devices, the kernel can encounter variations in mixture fraction as it travels through a region where air and fuel mix. In other words, the probability that the kernel will lead to flame propagation is high if an ignition source of sufficient energy is placed near a mixture within the flammability limits [6]. In many practical systems, however, such as aircraft engine main combustors or afterburners, the igniter is generally located near a wall where the local composition can be outside the flammability limits [6]. In these cases, the probability of ignition depends upon the conditions through which the kernel must travel before it reaches a flammable mixture. Thus the goal of this work is characterization of a spark kernel in air and understanding its evolution. Both experimental and numerical methods are employed to this end, with the intent that a validated modeling approach can be used in future ignition studies.

2 Methods

2.1 Experimental Setup

Measurements were acquired from a short duration, high energy spark discharge in an opposed electrode configuration. The discharge was characterized with 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 cylindrical copper electrodes. The diameter of the copper electrodes (3.18 mm) was chosen to produce low impedance, and the gap spacing was 6.4 mm to ensure a high breakdown voltage. The high energy, short duration discharge is created by a modified Metalaser 2051 copper vapor laser 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 Tektronix P6015A high voltage probe. Current through the electrodes was measured 10 cm from the gap on the cathode side using a Pearson model 6600 current monitor with a 5 ns response.

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

Figure 2: Measured voltage (V) and current (I) time traces as well as integrated energy delivered (E).

\[ E_{\text{supplied}} = \int V(t)I(t)dt \]  

2.1.2 Flow Calorimeter and Deposited Energy Measurements

In order to measure what fraction of the supplied electrical energy is deposited into the flow, a special calorimeter was developed. The electrodes are placed in a rectangular channel (19 mm wide \( \times \) 31.8 mm tall cross section) shown schematically in Fig.3. The supplied air flow first passes through a perforated plate and development section to produce a nearly uniform flow. Just before the test section, wire screens are placed to control the turbulence level at the electrodes. High turbulence conditions were produced by placing a small bluff body upstream of the electrodes, but downstream from the wire screens. The electrodes are introduced through the top and bottom walls of the test section, 25 mm downstream of the turbulence screens. The test section has full-view quartz windows on opposite sides. To reduce heat losses, the 12.7 cm long channel downstream of the electrodes was wrapped in fiber glass insulation, and the steady-state heat loss was calculated to be 0.5% of the supplied electrical power.

The flow temperatures were measured upstream and downstream of the electrodes, as depicted in Fig.4, with thermistors. The distance to the downstream measurement location was chosen
such that the heated portion of the flow had grown, on average, to be nearly the width of the channel. With the spark kernel having mixed with a significant amount of the surrounding air, the maximum temperatures experienced by the thermistors were significantly reduced. In addition to the flow temperatures, the velocity at the downstream location was obtained with a pitot probe. Temperatures and velocities at the downstream station were measured at a number of points to characterize the nonuniform flow produced by the discharge. The thermistors time response was not sufficient to capture the time-varying temperatures produced by the pulsed discharge. Instead, measurements were acquired only after the calorimeter had achieved quasi-steady operation, and the time-varying temperature from the thermistor was time-averaged to obtain the thermal energy of the flow. Additionally, the calorimeter data was obtained with the discharge firing at a high repetition rate ($100 - 300 \text{ Hz}$) to make sure that the thermistor temperature rise was sufficient to produce accurate energy measurements. The velocity and temperature data were converted to the deposited thermal energy with the energy balance described by Eq.2. Combining the uncertainties in the temperature, velocity and electrical measurements, the propagated uncertainty [12] in the energy deposition efficiency (energy deposited/energy supplied) was calculated to be less than 5%.

$$E_{\text{deposited}} = \frac{1}{f_{\text{rep}}} c_p \int_{\text{exit}} \frac{p}{RT_2} u_2 (T_2 - T_1) dA$$  \hspace{1cm} (2)
2.1.3 High Speed Schlieren and Emission Imaging

The evolution of the spark kernel was characterized with a combination of high-speed schlieren and emission imaging. The kernel was viewed through the quartz windows on the sides of the test section. The single pass collimated schlieren system (Fig.5) uses a 50 W halogen light source. The light passes through a 0.4 \text{mm} diameter pin hole and is then collimated by a 0.2 m diameter, 1 m focal length off-axis parabolic mirror. The reflected collimated light is directed to a flat mirror, which redirects the light at right angles through the test section. The rays are redirected once again toward a second (identical) parabolic mirror. This mirror refocuses the light to a point. The schlieren stop was produced by a glass slide with an opaque spot, roughly the size of the focus of the light beam with the flow facility not running.

![Figure 5: Schematic of the Schlieren imaging system: LS-light source, PM-parabolic mirror, M-mirror, S-Schieren stop, C-high speed camera.](image)

A high speed CMOS camera (Photron Fastcam SA3) focused on the test section is used to record the data. An 80 mm telephoto photographic lens with a 2 \times teleconverter was mounted on the camera, and a 200 mm diverging lens was placed in front to correct for refraction through the focusing mirrors. A digital delay and pulse generator (SRS DG535) was used to trigger the discharge and the camera, with a delay between the two triggers (Fig.6). This allows the spark to fire just before the camera exposure begins. The framing rate of the camera was set to 250 Hz. Combined schlieren and spark emission images are obtained with the halogen light source operating. With the light source off, images containing only the kernel emission were acquired.

2.2 Numerical Approach

In order to gain additional insight into the process of spark kernel development, an LES numerical study was performed for the same opposed electrode geometry employed in the experiments. A grid containing 5.6 million points was constructed for the rectangular channel. The electrodes were modeled as circular cylinders, which necessitated the use of a cylindrical coordinate system in the vicinity of the electrodes, smoothly merging with a Cartesian system throughout the rest of...
the channel. The highest resolution was located between the electrodes, with a minimum distance of 30 \( \mu m \) between nodes. A no-slip boundary condition was imposed on the cylinder and channel walls, and a subsonic non-reflecting boundary condition was placed at either end of the channel to allow for shock propagation. The simulations were performed for a 33 \( m/s \) cross-flow of air at 300 \( K \) and 1 \( atm \), essentially the same as the conditions of the experiment.

The detailed electrical energy discharge process was not modeled. Rather the discharge was approximated by an essentially instantaneous event that creates a cylindrical volume of high-temperature, high-pressure gas along the full length of the axis between the electrodes. A nominal diameter of 1.0 \( mm \) was chosen for this spark kernel channel. Given the short duration and uniform nature assumed for the discharge, the initial density of the channel was constrained to be the same as the air density preceding the discharge. In addition, the channel was assumed to be in thermal equilibrium. Using the prescribed density and the requirement that the thermal energy rise in the channel (above the background air energy) match the \( \sim 0.25 J \) of energy deposited during the discharge, the other channel conditions, i.e., temperature and pressure, can be calculated for a given composition. Cases with a chemical equilibrium composition (including ionized species) were calculated using the NASA CEA solver. In addition, non-equilibrium composition cases were also examined. This high-temperature spark volume was then introduced into the flow and allowed to develop over the total simulation time \( \sim 200 \mu s \).

The simulation was performed using a hybrid integration scheme where upwind fluxes were computed using MUSCL-reconstruction and central fluxes were evaluated using fourth-order MacCormack integration. This hybrid approach allowed for the shock produced by the spark discharged to be resolved while appropriately calculating the flux in the rest of the flow. An 11 species, 30-step plasma air chemistry was derived from previous studies [13]. The chemical source terms were calculated using Euler integration.

### 3 Results and Discussion

#### 3.1 Energy Deposition

Example profiles of velocity \( (u_2) \) and temperature increase \( (T_2 - T_1) \) obtained during the energy deposition measurements are provided in Fig.7. The velocity is relatively uniform across the calorimeter exit, and, as expected, the hot region is centered in the middle of the cross-section.
where the electrodes are located. The hot gas has expanded to reach the side walls of the rectangular channel, but does not extend all the way to the top and bottom walls. In addition, the temperature profile is elongated in the horizontal dimension. This is due in part to the enhanced mixing caused by the wake behind the vertical electrodes. Additionally, the horizontal surfaces of the electrodes block expansion of the spark kernel in the vertical direction, as will be discussed below. Therefore, the hot region spreads more in the horizontal direction.

The deposited energy efficiency, as calculated using Eq.3, was above 90% for the entire range of velocities and turbulence intensities as summarized in Table 1.

\[
\eta_{\text{dep}} = \frac{E_{\text{thermal}}}{E_{\text{electrical}}}
\]  

Figure 7: Example measured velocity and temperature profiles for calorimeter exit plane.

Table 1: Deposition efficiency measurements for three flow conditions.

<table>
<thead>
<tr>
<th>Flow Velocity ([m/s])</th>
<th>Turbulence ((u'/u))</th>
<th>Energy Deposition Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>0.05</td>
<td>97%</td>
</tr>
<tr>
<td>33</td>
<td>0.05</td>
<td>96%</td>
</tr>
<tr>
<td>8</td>
<td>0.26</td>
<td>93%</td>
</tr>
</tbody>
</table>

The flow dynamics have little effect on the energy deposition because the spark duration is less than one microsecond, which is much shorter than any characteristic time scale for the flow. The short duration of the discharge is also a likely reason the energy deposition is high. Other causes for the measured high efficiencies include the use of low resistance electrodes with a gap situated far from a wall where heat transfer could occur. Fast response measurement probes located very close to the spark gap also improve measurement accuracy of the supplied electrical energy. Accurate energy deposition data are essential for the physical understanding of the kernel development process and to provide initial conditions for related numerical modeling.
3.2 Kernel Initialization for LES

As noted in the Methods section, the deposited energy results were used to provide an initial condition for the LES calculations. The nominal value of the initial kernel diameter (1 mm) was based on estimates of final spark channel widths. The sensitivity of the kernel development to the assumed kernel diameter was determined by varying the diameter while maintaining the total energy deposited constant. Thus the energy density changes inversely with the diameter. LES results for three initial diameters are shown in Fig.8. The figure shows the kernel volume as a function of time after the discharge, with the volume based on regions where the temperature is above 600 K (with the background air temperature at 300 K). As seen in Fig.8, the kernel volume grows rapidly in the first 20 µs, with the kernel volume essentially independent of the initial spark channel diameter. Even after 200 µs, there is only a small difference between the three cases. Thus we conclude that the simulation is not sensitive to the initial diameter choice; it is more important to know the correct kernel energy in order to predict the kernel development accurately.

Figure 8: LES results of kernel volume development for three initial kernel diameters.

This initial rapid rise in kernel size observed in Fig.8 is due to a pressure-driven expansion resulting from the high initial pressure in the kernel. The volume increase slows drastically before 10 µs when the kernel front reaches the edge of the electrodes. The kernel then begins to interact with the edges, allowing the shock front to decouple from the kernel and continue to propagate outwards as shown in Fig.9. This initial pressure wave is influenced by the amount of energy initialized in the kernel.

The sensitivity of the simulations to the initial composition was also investigated. Three initial conditions were selected with the same total energy and ratio of atomic nuclei (i.e. \( N : O = 3.76 : 1 \)). A zeroth order simulation of composition development in time was carried out for three different initial temperatures, each with its own radical composition: a 20,000 K case with high concentrations of \( O \) and \( N_2^+ \); an 18,000 K case with significant \( O^+ \) and and \( N_2^+ \) levels; and a 14,000 K case with high concentrations of \( O^+ \) and \( N^+ \). Fig.10 shows how the mass fractions of \( NO \) and \( N^+ \) develop for these three initial conditions. By 1 µs, the mass fractions approach similar
levels (15-21% for $N^+$ and $1 - 8 \text{ ppb}$ for $NO$). This suggests that the high chemical reaction rates at these conditions, especially for the ionized species, leads to rapid quasi-equilibration for most of the radical species. Thus we find the simulations are not strongly sensitive to the initial composition of the kernel as long as the deposited energy matches, at least not for time scales of interest to the kernel evolution process. For example, $1 \mu s$ is typically less than a characteristic simulation time step in the LES.

3.3 Kernel Evolution

Example schlieren images of the spark kernel evolving in air are shown in Fig.11. Here, the nominal flow velocity was $33 \text{ m/s}$ with a turbulence intensity of 5%. The camera was set to a framing rate of $250 \text{ Hz}$ with an exposure time of $\sim 33 \mu s$. Approximately 500 images were gathered for each delay time between the spark discharge and camera shutter opening. These delays were varied between 60 and $210 \mu s$ in steps of $10 \mu s$. The bright intensities in the first
Figure 11: Representative set of sequenced images from high speed schlieren recording of kernel development; times represent the delay between the spark breakdown and the image, with the image exposure lasting 33 $\mu$s. The green contours are added to emphasize the schlieren intensity distribution.

several images (up to $\sim 100 \mu$s) are due to visible emission from the plasma kernel. The dim visible light in the images represent the line of sight density gradient in the flow. At each delay time edge tracking was performed using a MATLAB routine. The grayscale images were converted into binary (black and white) images using a calibrated intensity threshold. This threshold was held constant for all images since it represents a specific density gradient in the schlieren images. This edge denotes the interface between the spark kernel and the ambient flow, and is included as the green contour shown in Fig.11.

The structure of the kernels can infered from these line-of-sight integrated images based on emission location and fine structures in the schlieren images. The kernel develops from an expanding cylinder into a toroid like shape. For example, this can be seen in the two-lobe structure in the kernel appearing around $80 - 90 \mu s$. The images at 80 and 90 $\mu s$ also shows that the light emitted by the high temperature kernel is more pronounced in the downstream lobe of the kernel. This suggests that the high temperatures survive longer in this region compared to the upstream portion of the kernel.

Using the interpreted kernel geometry, along with the line of sight integrated area obtained from the schlieren images, the volume of the kernel was estimated. An equilibrium code (NASA CEA) was then used to convert the measured volumes to kernel temperatures. Although equilibrium was assumed, air plasma species were used, including: $N_2, O_2, NO, N, O, N^+_2, O^+_2, N^+, O^+, NO^+$, and $e^-$. Based on a constant pressure of 1 atm, the temperature was varied between 300 and 10,000 K.
Based on the electrical energy measured for the current system, an input energy of $0.25 \text{ J/pulse}$ was used in conjunction with Eq.4 to create a temperature-volume look-up table.

$$\Delta h(T_{\text{kernel}}) = \frac{E_{\text{dep}}}{(p/RT_{\text{kernel}})V}$$ (4)

The evolution of the kernel temperature was generated using the volumes obtained from the schlieren images and assuming uniform temperature in the kernel. Fig.12 shows a rapid decrease in temperature of the kernel within the first $100 \mu \text{s}$, with temperature stabilizing around $1700 - 1800 \text{ K}$ at $250 - 300 \mu \text{s}$. The error bars were generated from the propagation of uncertainty from the kernel dimension measurements.

![Figure 12: Calculated temperature evolution of kernel between 60 $\mu \text{s}$ and 300 $\mu \text{s}$ following the spark discharge.](image)

The volumes used in Fig.12 are only estimates obtained from the line-of-sight schlieren images, assuming the kernel is axisymmetric about a central vertical axis with an assumed shape. For a more direct comparison with the LES predictions, the total area contained within the schlieren defined boundaries was also determined for each image. At each delay time, the 500 images were processed, capturing the distribution of kernel area for those times. For comparison, snapshots from the numerical simulations were analyzed to produce similar area predictions.

Two approaches were used to examine the LES data. The first is based on two-dimensional slices of the predicted kernel density taken at a streamwise plane passing through the electrode axis and extending from upstream of the electrodes to well downstream. These slices, at delay times roughly corresponding to the schlieren images of Fig.11, are shown in Fig.13. The same edge tracking analysis used for the experimental data was applied to the LES images to generate the edge contours shown in the figure. The second approach uses line-of-sight integrated images based on the predicted kernel density gradients. This approach more closely models the physical process behind schlieren imaging. Fig.14 shows images of the three dimensional density gradients in the
Figure 13: Line-of-sight integrated (3D) “images” of the spark kernel density gradient at six delay times.

Figure 14: Sequenced set of two-dimensional density “images” from the numerical simulation.

simulated kernel at six delay times. Again, the edge tracking analysis was used to produce the contours shown.

A comparison between the measured and calculated kernel areas is shown in Fig.15. The experimental (schlieren) results show a moderate increase (about 25%) in mean area from $60 - 210 \mu s$. The error bars were generated using the standard deviations calculated from the area distributions of the 500 images obtained at each point. The area results obtained from the two-dimensional LES density slices show a rapid expansion within the first $40 \mu s$ and then an oscillatory pattern (no corresponding experimental data could be obtained during the first $40 \mu s$ because of the intense radiation from the spark). The fluctuations in the LES-based area are caused by significant variations in the shape of the centerline plane, caused by reflecting pressure waves changing the background density (see below). The areas determined from the 3D density gradient agree remarkably well with the experimental data. Both show the same relative increase in the projected kernel area,
though with the LES density gradient results a little lower than the experimental data. Still, the agreement between the experimental and numerical results is evidence that the simulations capture the development of the kernel, and that the LES results can be used to elucidate the processes controlling the kernel evolution.

Some aspects of the kernel evolution can be understood by reviewing the density results of Fig.14. For example, it appears that pressure waves reflect off the walls and return to the central plane, altering the shape of the kernel at times well after the discharge has ended. This causes a fluctuation in the density that alters the apparent kernel size. This effect is visible for the images at 110 µs and 121 µs. It is possible, however, that the reflections in the experimental system are damped more than in the computational study. Additionally, the LES results support the interpretation that the kernel develops a toroidal shape after $\sim 60$ µs. Examination of the calculated velocity field shows that when the expanding pressure waves move out beyond the edges of the electrode, air is drawn downward along the vertical electrode surfaces. Thus cold surrounding air is entrained into the central region of the expanding kernel. The vorticity created at these early times survives as the kernel develops, continuing the entrainment of cold air into the center of the kernel producing the toroidal shape. This entrainment is the primary reason the kernel grows after the first $30−50$ µs and the source of the rapid drop in temperature observed in Fig.12. In addition, enhanced entrainment in the upstream lobe of the kernel causes the enhanced temperature decay observed in the light emission images.

4 Conclusions

The evolution of a high energy spark kernel was investigated experimentally and numerically. The electrical energy supplied to the electrodes was measured close to the spark gap and compared to the energy deposited in the gas through the use of a flow calorimeter. The deposition efficiency was above 90% for all cases and was not significantly influenced by flow velocity or turbulence intensity. This is not surprising considering the short duration of the discharge ($<1$ µs) compared to characteristic convection and turbulence times. Evolution of the kernel was tracked experimentally
using high speed schlieren and emission images synchronized with the spark events. The high temperatures in the kernel decay rapidly, with average temperatures in the kernel estimated to be less than $2000 \, \text{K}$ within a few hundred microseconds.

Large eddy simulations were used to model the kernel evolution. A simple method for initializing the kernel was validated. The breakdown and discharge processes are reduced to an instantaneous energy deposition process in a cylindrical volume extending between the opposed electrodes. The deposited energy was matched to the measured values, and this parameter was found to be the most important in properly predicting the kernel evolution. Thus accurate measurements of deposited energy can be crucial to developing accurate ignition predictions. The growth of the kernel after a few microseconds was found to be only weakly dependent on the assumed initial kernel diameter and composition. The decreased energy density associated with a larger initial kernel size produces a lower pressure and weaker initial expansion which eventually matches the expansion produced by a smaller kernel with the same deposited energy. Similarly at the high temperatures associated with the initial kernel conditions, the reaction rates are sufficiently fast that the composition at later times is only weakly dependent on the assumed initial composition.

The LES results were validated by comparisons to measurements of the shape and size of the kernel, and their evolution. Both the experiments and simulations show that the kernel rapidly develops into a toroid-like shape as it is convected away from the electrodes. The interaction of the expanding pressure waves with the electrodes induces vorticity and entrainment that mixes cold surrounding air into the central region of the expanding kernel. This entrainment is the primary reason the kernel grows after the initial pressure-based expansion ends. In addition, the LES results correctly capture the enhanced mixing in the upstream portion of the kernel, which cause the temperatures to drop more rapidly there. The fact that the downstream lobe exhibits higher temperatures as the kernel evolves suggests it is likely that this region would be the dominant source of ignition when the kernel produced in the current electrode geometry comes upon a flammable mixture. The success of the LES approach for modeling the kernel development also bodes well for its success in modeling ignition of non-premixed combustion systems.

Acknowledgments

The authors gratefully acknowledge support for this work from Pratt and Whitney (PW) through the PW-GT Center of Excellence.

References


