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Statistical Analysis of Electrostatic Spark Ignition

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Determining the risk of accidental ignition of flammable mixtures is a topic of tremendous importance in industry and aviation safety. The concept of minimum ignition energy (MIE) has traditionally formed the basis for studying ignition hazards of fuels. In recent years, however, the viewpoint of ignition as a statistical phenomenon has formed the basis for studying ignition, as this approach appears to be more consistent with the inherent variability in engineering test data. Ignition tests have been performed in lean hydrogen-based aviation tests mixtures and in two hexane-air mixtures using low-energy capacitive spark ignition systems. Tests were carried out using both short, fixed sparks (1 to 2 mm) and variable length sparks up to 10 mm. The results were analyzed using statistical tools to obtain probability distributions for ignition versus spark energy and spark energy density (energy per unit spark length). Results show that a single threshold MIE value does not exist, and that the energy per unit length may be a more appropriate parameter for quantifying the risk of ignition. The probability of ignition versus spark charge was also investigated, and the statistical results for the spark charge and spark energy density were compared.

1 Introduction

Determining the incendivity of flammable mixtures is a topic of great importance in industrial and aviation safety. A large amount of work has been done over the past several decades to quantify the risk of ignition of many different fuels and mixture compositions. The traditional method of assessing the risk of ignition has been to determine a minimum ignition energy (MIE) using capacitive spark discharges [1–4]. The pioneering work using this method was performed in the 1940s and 1950s at the Bureau of Mines by Blanc, Guest, Lewis and von Elbe [5–8]. They obtained MIE values for many different fuels using capacitive sparks with a fixed electrode gap, and this work is still cited extensively in the literature. Subsequent work on determining MIE values, for example [9–13], have used similar methods to determine the threshold energy for ignition at a fixed spark gap.

The viewpoint of ignition energy as a threshold value has traditionally formed the basis for studying ignition in combustion science. However in recent years, particularly in the aviation industry, it has been proposed that ignition is actually a statistical phenomenon, which is more consistent with the variability in ignition test data. There has been some work done on the statistics of ignition of Jet A [14] and hot surface ignition of liquid fuels [15], but little or no work has been done on investigating the statistical nature of ignition of gaseous fuels. In this work we first investigate statistical nature of ignition in three lean hydrogen-based aviation test mixtures. Ignition tests are performed using a range of spark energies, and statistical tools are used to obtain probability distributions for ignition versus spark energy.

In the second phase of this work, the dependence of ignition not only on spark energy but also on the length of the spark is examined. The use of energy density, i.e. the parameter E/d where E is the spark energy and d is the spark gap length, to characterize incendivity was recently proposed by von Pidoll et al. [16]. To examine the dependence of ignition on energy density, ignition tests are performed in one of the lean hydrogen-based test mixtures as well as two hexane-air mixtures using a range of spark energies and spark lengths. Statistical tools are then used to obtain probability distributions for ignition versus the spark energy density. Finally, von Pidoll et al. also suggest the use of charge to quantify incentivity of electrostatic discharges instead of energy-based parameters based on the argument that the charge is less dependent on the voltage and discharge gap. To examine this concept, probability distributions for ignition versus the spark charge are obtained and compared with the results versus energy density.

2 Probability and Historical Spark Ignition Measurements

The large volume of historical minimum ignition energy data for capacitive spark discharge ignition referenced in Section 1 has been extensively used in the chemical and aviation industry to set standards and evaluate safety with flammable gas mixtures. However, there is scant information on the experimental procedures, raw data or uncertainty consideration, or any other information that would enable the assignment of a statistical meaning to the minimum ignition energies that were reported. However, some researchers have claimed that the historical data can be interpreted as corresponding to a certain level of ignition probability. For example, in a paper by Moorhouse et al. [12] the authors claim that the MIE results of Lewis and von Elbe [5], Metzler [9, 10], and Calcote [11] all correspond to an ignition probability of 0.01.

In the work by Metzler cited in Moorhouse et al., the author studied ignition of several fuels using a capacitive spark discharge circuit that includes a resistor in series with the spark gap to vary the energy supplied to the gap. The minimum ignition energy for a given gap width was determined by increasing the spark energy by adjusting the voltage and resistance until ignition was achieved by a single spark. The number of tests performed is not stated, and the author does not address probability of ignition at all in the reports. In the work by Calcote et al. cited in Moorhouse et al., the authors examined the minimum ignition energy for a large number of fuels with varying molecular structure. The experimental procedure described in the paper involves charging a capacitor with known capacitance through a high resistance until a spark passes between the electrodes. Instead of varying the capacitance, the authors instead kept the capacitance constant and varied the electrode distance until the threshold energy was obtained, providing one point on the curve of ignition energy versus electrode distance. The minimum of the curve was then taken as the minimum ignition energy. As with Metzler, the number of tests is not stated and the concept of an ignition probability of 0.01 is never discussed. Finally, Moorhouse et al. reference the work done by Lewis and von Elbe as described in [5] and first published in three papers in the late 1940s [6–8]. The procedure to determine the minimum ignition energy is described in detail in [5] and involves gradually increasing the capacitance until ignition occurs for a fixed electrode gap. The procedure is repeated for different electrode distances to obtain a curve of the minimum ignition energy versus gap distance. There is no mention in either [5] nor in any of the three papers of ignition probability or a 1% probability criteria. In addition, ignition probability is never discussed in any of the Bureau of Mines reports [17–23] on their work in determining MIE values.

Therefore, it is impossible to prescribe probabilities to historical minimum ignition energy data, as probabilities were never addressed in the literature and there is not enough information on the number of tests performed and the experimental procedures.

3 Statistical Analysis

In traditional MIE testing, the goal is to obtain a threshold spark energy above which ignition of the mixture will always occur and below which ignition will never occur. In this work, ignition is instead viewed as a statistical phenomenon, so the goal is to obtain a probability distribution for ignition rather than a threshold energy value. In this work we use the logistic regression method [24] to obtain a cumulative probability distribution for ignition test data. The logistic distribution model has been used by others to characterize ignition of liquid aviation and automotive fuels [15]. It is also advantageous to use this model because it is simple computationally as likelihood-based inference methods can be used to estimate the distribution parameters.

The spark ignition tests are assigned a binary result y, where $y = 1$ when ignition occurs (a "go") and $y = 0$ when ignition does not occur (a "no go") for a given stimulus level x (i.e. spark energy density or spark charge). The cumulative probability distribution for ignition (a "go") versus stimulus level x is then defined as:

$$P\left(x\right) = \text{Probability}\left(y = 1; x\right) \ . \tag{1}$$

The results for n tests can be represented collectively using the likelihood function:

$$L = \prod_{i=1}^{n} P\left(x_i\right)^{y_i} \left(1 - P\left(x_i\right)\right)^{1-y_i} \tag{2}$$

where x_i and y_i are the stimulus level and binary result for the i^{th} test, respectively. The probability $P\left(x\right)$ is represented by the parametric logistic distribution function:

$$P\left(x\right) = \frac{1}{1 + \exp\left(-\beta_0 - \beta_1 x\right)} \tag{3}$$

where β_0 and β_1 are parameters determined by maximizing the likelihood function (Equation 2). The $\left(100q\right)^{th}$ percentile, x_q is then:

$$x_q = \frac{1}{\beta_1} \ln\left(\frac{q}{1-q} - \beta_0\right) \ . \tag{4}$$

The limits for the $100\left(1 - \alpha/2\right)\%$ confidence interval for the percentile x_q can be calculated using the large sample approach for a two-sided interval:

$$UCL/LCL = x_q + / - Z_{\alpha/2} \sqrt{\left(\sigma_{00} + 2x_q\sigma_{01} + x_q^2\sigma_{11}\right)/\beta_1^2} \tag{5}$$

where σ_{00}, σ_{11}, and σ_{01} are the variances and covariance of β_0 and β_1, α is equal to 1 minus the confidence level (i.e. 0.95 for 95% confidence) and $Z_{\alpha/2}$ is the $100\left(1 - \alpha/2\right)\%$ percentile from a standard cumulative Gaussian distribution. This analysis results in a probability distribution for the n spark ignition tests and a confidence envelope on the probability of ignition versus the spark characteristic of interest.

4 Low-Energy Sparks

Traditional MIE testing used capacitive spark ignition systems with a fixed-length spark gap, and the goal was determining the minimum spark energy required for ignition using that particular gap size. In this work, however, our objective is to study the statistical nature of ignition with both fixed and variable spark lengths. Therefore, we first developed a low-energy spark ignition system to produce short sparks with a fixed length of 1 to 2 mm to study ignition versus spark energy. A second ignition system was then developed to generate sparks with variable lengths from 1 mm to 10 mm or longer to examine ignition versus spark energy density (spark energy divided by the spark length). We can also compare ignition versus spark energy or energy density with ignition versus spark charge, as measurement of the spark charge is possible with both ignition systems. This section briefly discusses the designs of the two ignition systems as well as determination of the spark energy and charge.

4.1 Short, Fixed-Length Spark Ignition System

In the first phase of this work ignition tests were conducted with short, fixed length sparks so that the probability of ignition versus spark energy could be determined and the results compared with previous MIE results. Therefore, a low-energy capacitive spark ignition system was designed to generate sparks across a fixed spark gap of 1 to 2 mm and with energies near the traditional MIE values, approximately 50 μJ to 1 mJ. The circuit design is based on the ideas of Ono et al. [13,25] and consists of a simple capacitive discharge circuit with several features to improve performance. A 3-30 pF variable vacuum capacitor is charged by a 0-15 kV high voltage power supply through two 50 GΩ isolation resistors. The voltage is ramped up slowly from 0 to 15 kV and when the breakdown voltage of the gap is reached the capacitor discharges across the gap, producing a spark. After the spark a relay disconnects the capacitor from the high voltage power supply to prevent multiple sparks. The breakdown voltage is measured using a high voltage probe and the spark current is measured using a fast current transformer. More details on the spark ignition system are presented in [26].

4.2 Variable Length Spark Ignition System

In the second phase of this work, the effect of spark length on ignition was examined. A second low-energy spark ignition system was developed to generate sparks with lengths varying from approximately 1 to 10 mm. The design of the second ignition system differed significantly from the fixed-length spark system, described in Section 4.1. In this circuit, a capacitor is formed by suspending an isolated circular aluminum plate with an electrode mounted on it inside the combustion vessel. The isolated plate was charged with a negative high voltage and the vessel walls acted as the capacitor ground. The capacitance could be varied from approximately 5 to 20 pF by changing the separation between the plate and the vessel wall or by changing the plate diameter. For ignition tests requiring higher spark energies, a 20-450 pF variable vacuum capacitor could be connected in parallel with the first capacitor. A high voltage power supply with a range of 0 to 30 kV was used to charge the capacitor(s) to the desired voltage through two isolation resistors. The power supply is then disconnected from the capacitor(s) and a grounded electrode is stepped toward the charged electrode on the capacitor plate using a motorized linear stage. When the grounded electrode reaches the breakdown distance it induces a spark across the gap. The spark length is varied by changing the charging voltage and the increasing or decreasing the capacitance gives a range of spark energies. By varying these parameters ignition tests can be performed using not only a range of spark energies, but also a range of spark energy densities, permitting the examination of the effect of spark length on ignition.

4.3 Determining Spark Energy and Charge

Traditionally, in spark ignition testing, i.e. [5], the spark energy was considered to be equal to the energy stored in the capacitor. However, there are many sources of energy loss (electromagnetic radiation, production of shock waves, residual energy in the capacitor, etc.) so only a fraction of the stored energy is delivered to the spark channel to heat the volume of gas and initiate combustion. These sources of loss are very difficult to quantify and depend strongly on the particular spark discharge circuit, so in this work we consider only the residual energy in the capacitor after the spark. Therefore we approximate the spark energy as the difference between the stored energy in the capacitor and the residual energy in the capacitor after discharge:

$$E_{spark} \approx E_{stored} - E_{residual} \tag{6}$$

where

$$E_{stored} = \frac{1}{2} C V_{breakdown}^2 \tag{7}$$

and

$$E_{residual} = \frac{1}{2} \frac{Q_{residual}^2}{C} \ . \tag{8}$$

The voltage on the capacitor at spark breakdown is measured using a high voltage probe, and the spark current is measured using a high-speed current transformer (Bergoz CT-D1.0-B) and recorded on an oscilloscope. The capacitance C includes not only the contribution of the capacitor but also the stray capacitance in the circuit due to electrical leads and the spark gap. To accurately determine the total capacitance, a Keithley 6517A electrometer was used. The capacitor was charged to 1 kV using the electrometer's precision power supply, then discharged using a grounded probe connected to the electrometer which records the charge. The capacitance is then calculated simply as

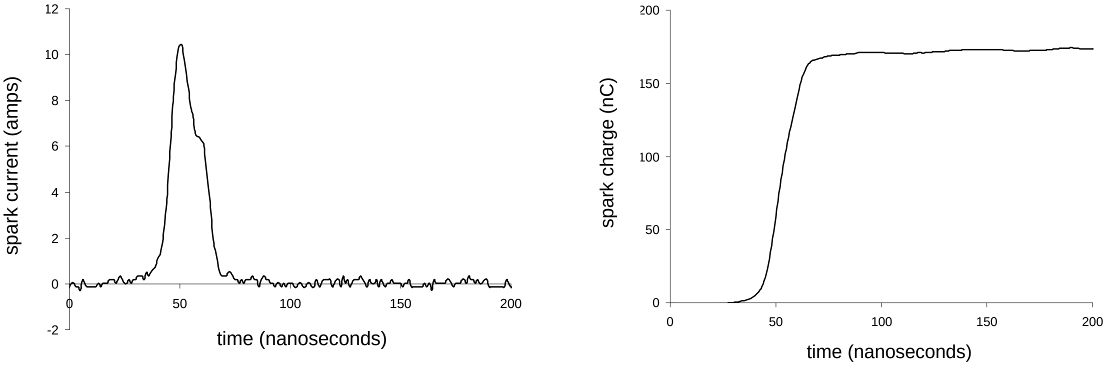
$$C = \frac{Q}{V} = \frac{Q_{electrometer}}{1000 \text{ V}} \ . \tag{9}$$

The residual charge in the capacitor, $Q_{residual}$ is calculated by subtracting the spark charge from the original stored charge,

$$Q_{residual} = Q_{stored} - Q_{spark} = C V_{breakdown} - \int i_{spark}(t)\, dt \tag{10}$$

where the integral of the spark current $i_{spark}\left(t\right)$ is calculated by numerical integration of the waveform from the current transformer.

In this work we want to consider not only the spark energy required for ignition, but also the spark charge. As already stated, the spark charge can be calculated directly by integrating the spark current waveform, as demonstrated in Figure 1. The spark charge can also be determined precisely using the electrometer by discharging the spark into a second capacitor and measuring the resulting charge on the capacitor. In this work we verified the spark charge calculations using the current trace by inserting a 10 nF capacitor between the spark gap and ground and taking measurements of the spark charge using the electrometer.



(a) (b)

Figure 1: (a) Current waveform from an example spark; (b) spark charge vs. time obtained by numerically integrating the current waveform.

4.4 Experimental Method

The spark ignition tests were conducted in a closed, rectangular combustion chamber approximately 11.75 liters in volume. The ignition system fixtures were mounted in specialized flanges on the walls of the chamber such that the spark gap was near the center of inside of the vessel. The chamber is first evacuated and then filled with the gaseous test mixture using the method of partial pressures. The pressure inside the vessel is continuously measured by a Heise 901A manometer with a precise digital readout so that the gases can be filled to within 0.01 kPa of the desired partial pressure. All plumbing lines are evacuated between gases, ensuring precise control over the test mixture composition. Windows in two of the vessel walls allow for visualization of the ignition.

To ensure reliable detection of ignition, three different methods were used. The primary method used to detect ignition was measuring the dynamic pressure inside the vessel using a piezoresistive pressure transducer. The transducer has high sensitivity so detection of any ignition event, even one with modest pressure rise, is ensured. A second method of detection is provided by a thermocouple recording the temperature rise inside the vessel following ignition. Finally, schlieren optics are used to visualize the flame through the vessel windows and video of the spark and subsequent ignition is recorded using a high-speed camera. More details on the test methods and the efforts to minimize experimental variability are presented in [26] and [27].

5 Results

5.1 Short, Fixed Spark Ignition Tests

Ignition tests were performed in the aviation test mixture recommended by the SAE in the Aerospace Recommended Practice (ARP) testing standards [3], 5% H_2-12% O_2-83% Ar. Ignition tests were also performed in two additional mixtures where the hydrogen concentration was increased by just 1%, 6% H_2-12% O_2-82% Ar and 7% H_2-12% O_2-81% Ar. The spark gaps lengths were fixed at 2 mm, 1.5 mm, and 1 mm for the 5%, 6%, and 7% H_2 mixtures, respectively, and the electrodes used were made of tungsten and conical in shape. The ignition test results were analyzed using the statistical tools described in Section 3, and the resulting probability distributions and 95% confidence intervals, as well as the regions of data overlap are shown in Figure 2. The energy with a 50% probability of ignition was 952 μJ for the 5% H_2 mixture, 351 μJ for the 6% H_2 mixture, and 143 μJ for the 7% H_2 mixture.

These results can be compared with the classic MIE results of Lewis and von Elbe [5], who obtained MIE curves for various hydrogen-oxygen-diluent mixtures. Lewis and von Elbe found the MIE of the 7% H_2 mixture to be approximately 100 muJ, which compares well with the 143 μJ found in this work. The 7% H_2 mixture was the leanest mixture for which Lewis and von Elbe presented an actual MIE data point, but they extrapolated the MIE curve to leaner compositions. According to their curve, the MIE for the 5% mixture is only 200 muJ, which is much lower than even the 10th percentile of the probability distribution found in this work. This difference can be explained by two factors, the first being that Lewis and von Elbe did not directly test the 5% mixture, but rather extrapolated a curve. The MIE curves are presented in [5] on a logarithmic scale, so even a small error in the slope of the extrapolated curve could drastically change the MIE values for mixtures leaner than 7% H_2. Also, the electrodes used by Lewis and von Elbe had glass flanges which contained the heated gas kernel for a longer period of time, producing ignition at lower energy values than with the conical electrodes used in this work.

5.2 Variable-Length Spark Ignition Tests

A second set of ignition tests were performed in the 6% H_2 test mixture using a range of spark lengths and energy densities. The test data points are shown in Figure 3(a). The spark energy with 50% probability of ignition from the fixed 1.5 mm spark tests, indicated by the dashed red line, was 351 μJ, while the median spark energy from the tests with variable spark lengths was 741 μJ with a 3.0 mm spark. This comparison demonstrates that the spark length does have a large effect on the energy required for ignition, and that a single threshold value or probability distribution cannot be applied to sparks of any length. Figure 3(b) shows the probability distribution for ignition versus the energy density (spark energy divided by length), centered (50% probability) at 154 μJ/mm. A comparison in terms of energy density can be made with the fixed spark tests by dividing the 50^{th} percentile energy from those tests (351 μJ) by the spark length (1.5 mm), giving an energy density of 234 μJ/mm. These two values for energy density are much more comparable than the values

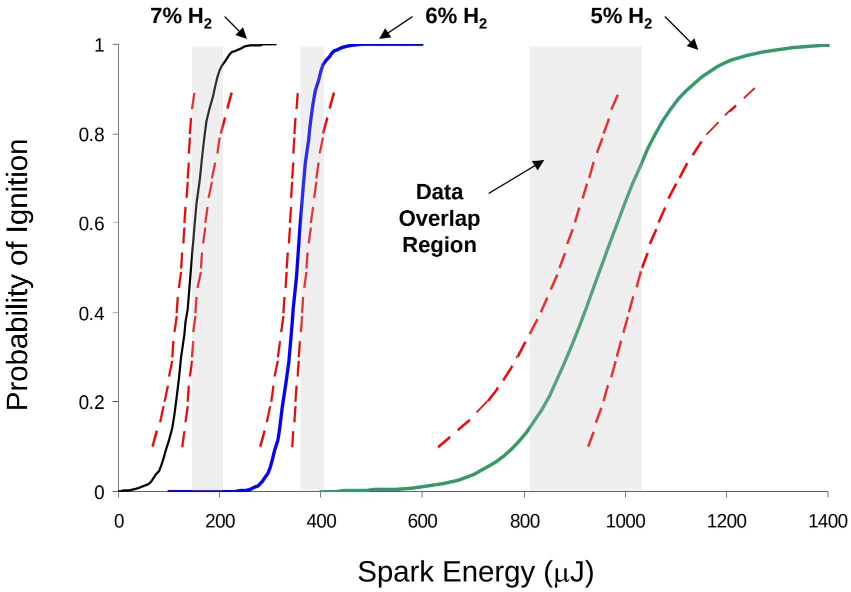
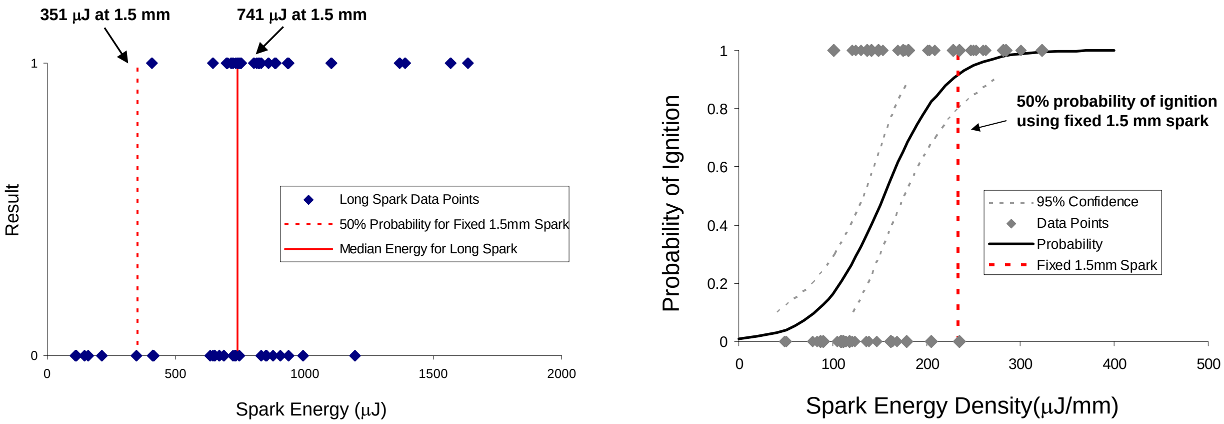


Figure 2: Probability distributions and for ignition versus spark energy for mixtures with 5, 6, an 7% H_2, 12% O_2 and argon. The 95% confidence intervals are indicated by the dashed red lines, and the region of data overlap (range of energies where both "go's" and "no go's" occurred) are shown in gray.

for spark energy. The difference in the values can be explained by the reduced effect of electrode quenching with longer sparks leading to a lower spark energy requirement for ignition, as well as increased occurrence of localized ignition with the longer sparks due to spark channel instabilities.

Ignition tests were also performed in two hexane-air mixtures: stoichiometric (2.16% C_6H_{14}) hexane-air and a mixture with equivalence ratio $\phi = 1.71$ (3.76% C_6H_{14}). The second mixture was chosen because according to Lewis and von Elbe [5] the overall minimum MIE value for hexane-air mixtures occurs with an equivalence ratio of approximately $\phi = 1.71$. The resulting probability distributions for ignition versus energy density are shown in Figure 4. The distributions are centered (50% probability) at 342 μJ/mm and 656 muJ/mm for the rich ($\phi = 1.71$) and stoichiometric ($\phi = 1.0$) mixtures, respectively. According to ignition energy curves in Lewis and von Elbe [5] the MIE for the $\phi = 1.71$ mixture is approximately 250 μJ and the MIE for the stoichiometric mixture is approximately 900 μJ. We cannot make compare this data with our results, however, because the gap length used in the Lewis and von Elbe tests is unknown, so the energy density cannot be determined. Also, there is no information on the ignition probabilities that correspond to the historical MIE data. However, the statistical analysis in this work demonstrates the large degree of variability in ignition of these hexane mixtures and therefore it may be inappropriate to use a single MIE value when assessing the risk of ignition.



(a) (b)

Figure 3: (a) Ignition test results versus spark energy for the 6% H_2 mixture, with the 50th percentile from the fixed 1.5 mm spark tests indicated by the red dashed line; (b) probability distribution for ignition versus spark energy density for the 6% H_2 mixture.

5.3 Spark Energy Density Versus Charge

It was suggested by von Pidoll et al. [16] that the charge is a more appropriate parameter than the energy or energy density for characterizing the incendivity of electrostatic discharges because it is less dependent on the voltage and gap size. To investigate this idea, we sorted our ignition test results for the 6% H_2 test mixture and the two hexane-air test mixtures by the spark length. The minimum spark charge and energy that caused ignition for each spark length was identified, and these minimum ignition values are plotted versus the spark length in Figure 5. While the values shown in the plot are not necessarily the absolute minimum ignition charge or energy for that spark gap, only the minimum values from the tests in this work, they can still provide insight into the dependence of the charge or energy required for ignition on the spark length. The minimum charge required for ignition is nearly constant over a large range of spark gap sizes for all three test mixtures, supporting the claim by von Pidoll et al. that the charge does not have a strong dependence on the voltage or gap size. In the plot of minimum spark energy for ignition, the energy required shows a marked increase with increasing gap size for the 6% H_2 and $\phi = 1.0$ hexane-air test mixtures, however not for the $\phi = 1.71$ hexane-air mixture. These results suggest that in some cases the charge may be less dependent on the voltage and gap size and therefore a more appropriate measure of incendivity.

Probability distributions for ignition versus the spark charge were calculated for the three test mixtures, and are shown next to the probability distributions versus spark energy density in Figure 6(a) and (b) (6% H_2 mixture), Figure 7(a) and (b) ($\phi = 1.0$ hexane-air mixture), and Figure 8 ($\phi = 1.71$ hexane-air mixture). To directly compare the broadness of the two distributions, and therefore the variability of the test results with respect to energy density versus charge, the energy density and charge must be normalized. We normalize the energy density and charge by dividing by the 50^{th} percentiles (50% probability of ignition). This normalization results in the probability versus $(E/d) \,/\, (E/d)_{P=0.50}$ and $Q/Q_{P=0.50}$ where (E/d) and Q are the energy density

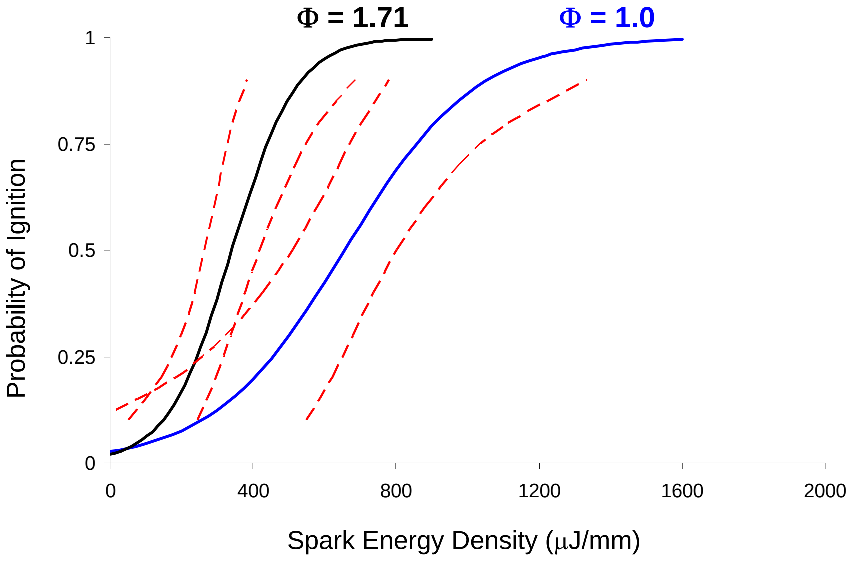


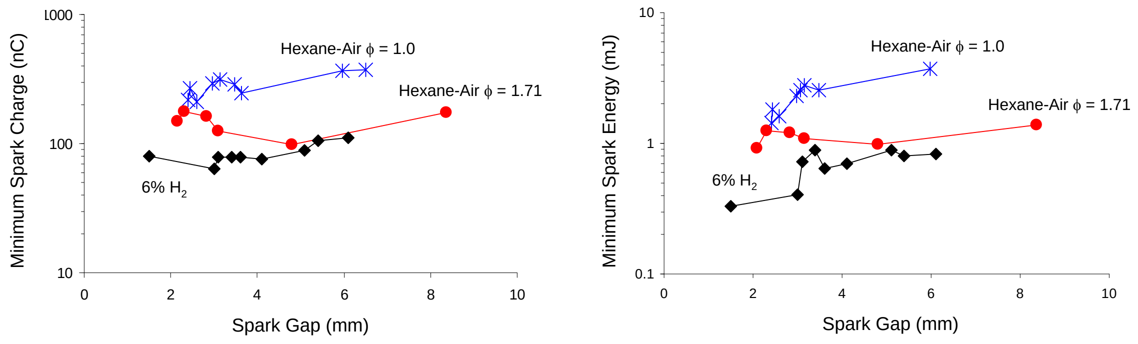
Figure 4: Probability distributions for ignition versus energy density for hexane mixtures with $\phi = 1.0$ (stoichiometric) and $\phi = 1.71$.

and charge, respectively, and $(E/d)_{P=0.50}$ and $Q_{P=0.50}$ are the energy density and charge corresponding to 50% ignition probability. The two probability distributions are then both centered at $(E/d)\,/\,(E/d)_{P=0.50} = Q/Q_{P=0.50} = 1.0$ and can be shown on the same plot for comparison, as in Figures 6(c), 7(c), and 8(c). For all three test mixtures, the probability distribution versus charge is significantly more narrow than the distribution versus energy density, demonstrating that ignition is less variable with respect to the spark charge. For a more quantitative comparison of the two distributions, we can compare the broadness of the two distributions by defining the “distribution width” as the difference between the 90^{th} and 10^{th} percentiles,

$$\text{“Width”} = \frac{(E/D)_{P=0.90} - (E/D)_{P=0.10}}{(E/D)_{P=0.90}} \tag{11}$$

$$= \frac{Q_{P=0.90} - Q_{P=0.10}}{Q_{P=0.50}}\,. \tag{12}$$

Using Equation 12, the normalized widths of the distributions for ignition versus energy are 0.94, 1.22, and 1.13 for the 6% H_2 mixture, stoichiometric hexane-air mixture, and rich ($\phi = 1.71$) mixture, respectively. The normalized widths for the distributions versus charge, however, are 0.50, 0.77, and 0.82. Therefore the normalized widths of the spark charge distributions are 27 to 47% smaller than the widths of the spark energy density distributions. Finally, Figure 9 shows a comparison of the spark energy and spark charge distributions for the ignition tests using short, fixed-length sparks. In these cases, the probability distributions versus charge shows no improvement over the distributions versus spark energy, due to the fact that in these tests both the voltage and the spark gap were held approximately constant. All these results support the idea by von Pidoll et al. that the charge may be a better characterization of the incendivity of the sparks for tests with varying voltage and gap distance, as the variability of the test results was reduced when



(a) (b)

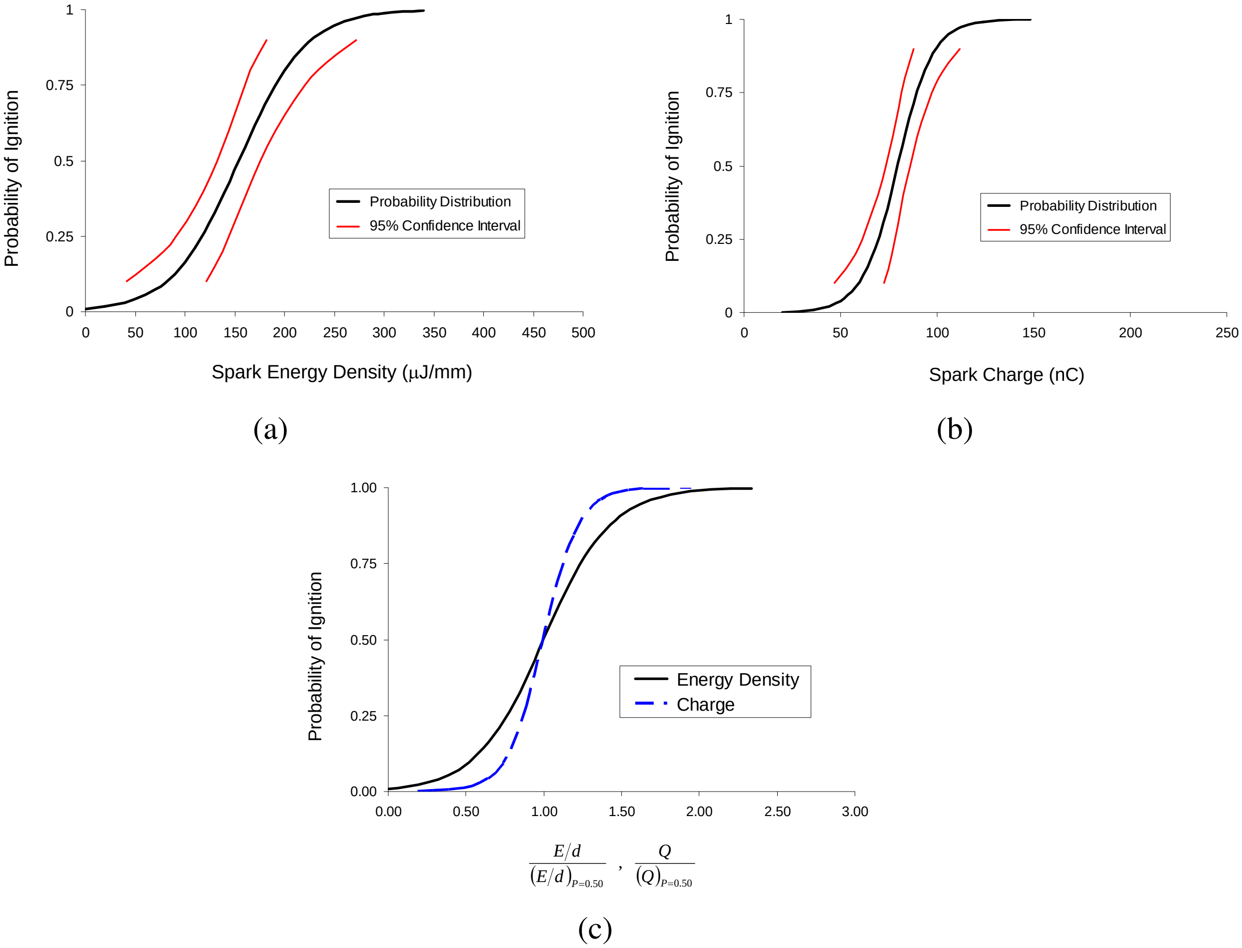
Figure 5: Approximate minimum spark charge (a) and spark energy (b) required for ignition versus spark gap length for the 6% H_2 test mixture and the two hexane-air test mixtures.

the probability was analyzed in terms of the spark charge versus the energy density.

6 Conclusion

In this work we studied the statistical nature of ignition in three lean hydrogen-based mixtures used in aviation testing as well as a stoichiometric hexane-air mixture and a rich ($\phi = 1.71$) hexane-air mixture corresponding to the minimum ignition energy for hexane in historical data. A low-energy capacitive spark ignition system was developed to produce short (1 to 2 mm) fixed-length sparks with energies near the traditional MIE values for hydrogen. Ignition tests were performed in three test mixtures with 5, 6, and 7% hydrogen over a range of spark energies, and the results were analyzed using statistical tools to obtain probability distributions for ignition versus spark energy. The results for the 7% hydrogen mixture compared well with historical MIE data, but the energy required for ignition for the 5% was found to be much larger than stated in the historical data.

A second capacitive spark ignition system was developed to produce variable-length sparks of 1 mm to 10 mm or longer. Ignition tests were performed in the 6% hydrogen mixture and in the two hexane-air mixtures using a range of spark energies and lengths. This procedure tested ignition versus spark energy density, E/d, a parameter proposed by von Pidoll et al. [16] for quantifying incendivity. Probability distributions for ignition versus spark energy density were obtained, and the results were compared with the fixed-length spark data (for the hydrogen mixture) and with historical data. The results demonstrated that ignition depends strongly on not just the spark energy but also the spark length, and therefore the spark energy density must be considered when assessing the risk of ignition. The probability of ignition versus the spark charge was also examined. The results were analyzed to investigate the hypothesis that the spark charge is a better measure measure of incendivity due to its small dependence on voltage and spark gap length, also proposed by von Pidoll et al. It was found that the probability distributions versus charge were less broad than the distributions versus the energy density, suggesting that ignition is less variable with respect to the spark charge. The results support further investigation into the use of charge for quantifying the incendivity of electrostatic ignition sources.

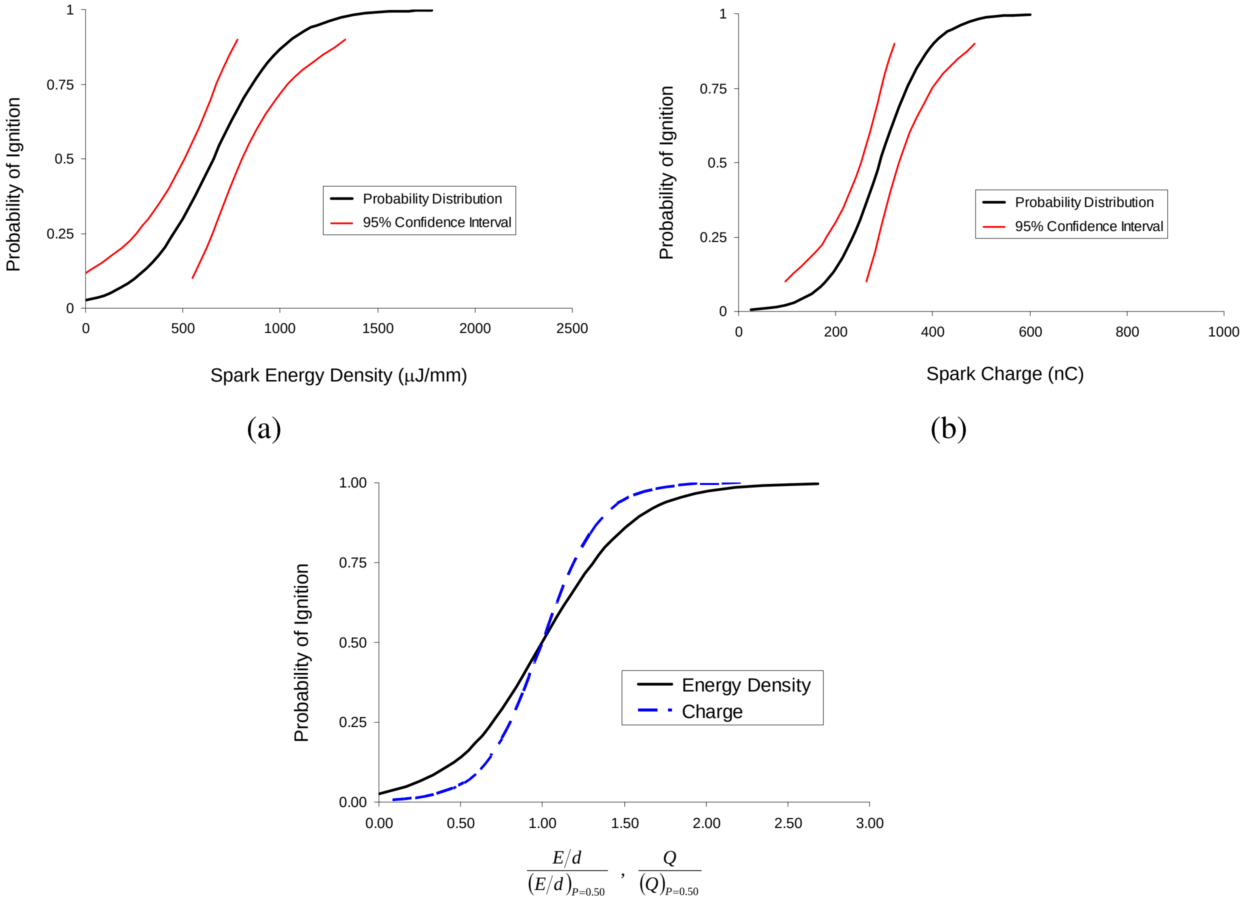


(a)

(b)

(c)

Figure 6: Statistical analysis of the ignition test results for the 6% H_2-12% O_2-82% Ar mixture. (a) Probability of Ignition vs. spark energy density; (b) probability of ignition vs. spark charge; (c) probability vs. normalized energy density and normalized charge shown on the same axis.



(a) (b)

(c)

Figure 7: Statistical analysis of the ignition test results for the stoichiometric (ϕ=1) hexane-air mixture. (a) Probability of Ignition vs. spark energy density; (b) probability of ignition vs. spark charge; (c) probability vs. normalized energy density and normalized charge shown on the same axis.

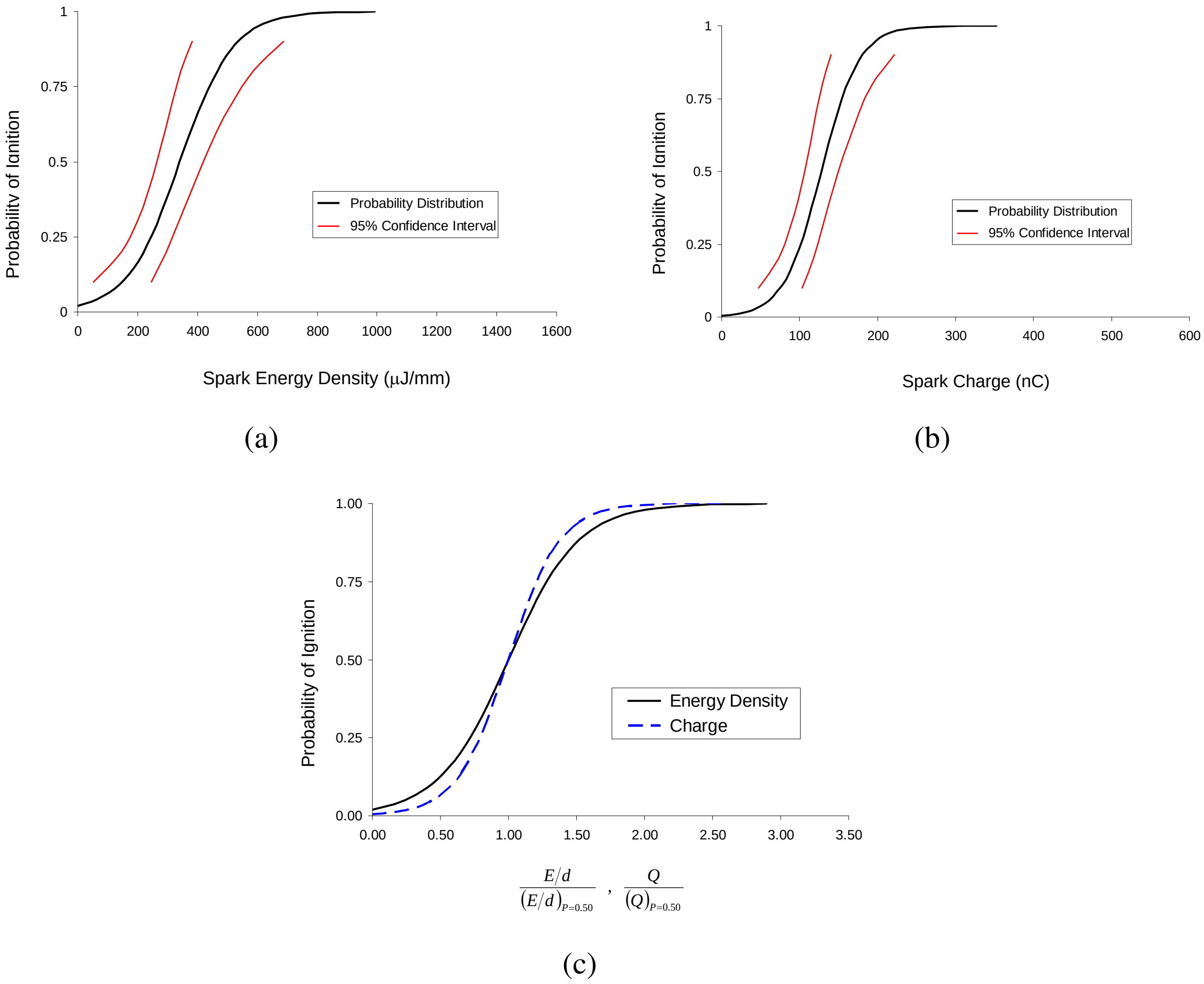


Figure 8: Statistical analysis of the ignition test results for the rich (ϕ=1.71) hexane-air mixture. (a) Probability of Ignition vs. spark energy density; (b) probability of ignition vs. spark charge; (c) probability vs. normalized energy density and normalized charge shown on the same axis.

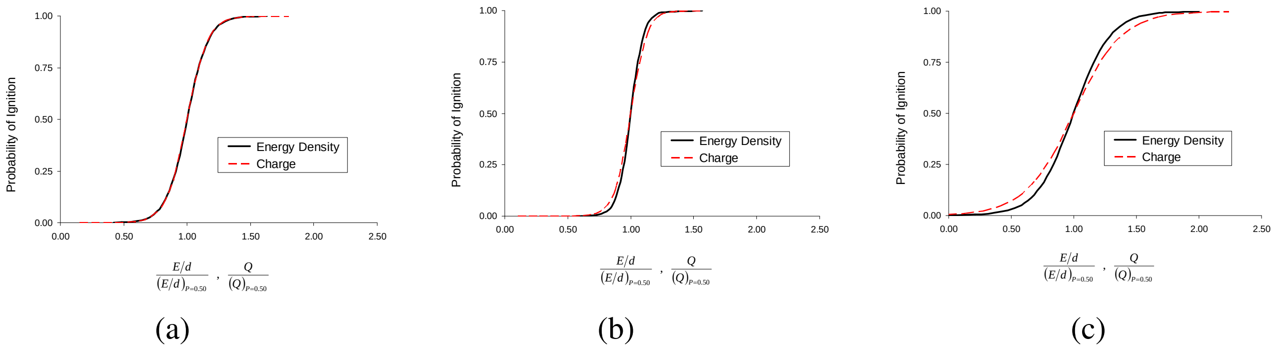


Figure 9: Comparison of the probability distributions for ignition versus normalized energy and charge for the short, fixed spark tests in the three hydrogen-based test mixtures. (a) 5% H_2; (b) 6% H_2; (c) 7% H_2.

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