TRANSITION REGION IGNITION CHARACTERISTICS OF N-HEPTANE FUEL SPRAYS

by

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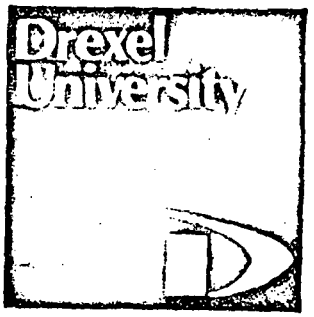

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ABSTRACT

Ignition studies were performed on monodisperse n-heptane sprays at atmospheric pressure over a range of equivalence ratios and droplet diameters. A capacitive discharge spark ignition system was used as the ignition source, providing independent control of spark energy and duration. Preliminary measurements were made to optimize spark duration and spark gap, optimum conditions being those at which the maximum frequency or probability of ignition was observed. The effect of spark duration on ignition frequency for several spark energies was determined for equivalence ratios of 0.5 and 1.0 and initial droplet diameters of 28 and 68 microns. Spark duration had little effect on ignition frequency over the entire 15-170 μs range examined. Spark durations of 70-80 μs were used for all subsequent work. The spark gap was optimized at equivalence ratios of 0.6, 0.8 and 1.0 and initial droplet diameters of 30, 40, 50, 60 and 70 microns by varying the electrode spacing from 0.5 to 5.0 mm while maintaining a constant spark energy. The optimum gap was determined to be 3.0 mm for nearly all conditions.

Using the optimum electrode spacing and spark duration, the frequency of ignition was determined as a function of spark energy for the same three equivalence ratios (0.6, 0.8, and 1.0) and for initial droplet diameters of 40, 50, 60, and 70 μm. The spark energy which led to a frequency of ignition of 90 percent was evaluated and defined as the minimum ignition energy. These data indicate that the ignitability of the sprays is enhanced as the equivalence ratio is increased from 0.6 to 1.0, as evidenced by a decrease in minimum ignition energy from 2 - 2.6 mJ to 0.6 - 1.0 mJ depending on droplet size. There is an initial uniform and consistent increase energy with increasing droplet size (from 40 -50 μm). This is followed by a slight decrease and then a subsequent increase in minimum ignition energy as the

droplet size is increased further. This local minimum in the ignition energy curve occurs near 60 μm for $\phi = 0.6$ and shifts to larger initial droplet diameters with increasing equivalence ratios. The effect of increasing spray velocity was to increase the minimum ignition energy, as expected.

I. INTRODUCTION

The combustion of liquid fuel sprays is expected to remain a major source of energy well into the twenty-first century. However, fuel properties and quality are currently deteriorating. It is anticipated that the fuels of the future may have properties which are significantly different from today's fuels. In order to effectively design fuel injectors, combustors, and ignitors to accommodate broadened specification and synthetic fuels, a more fundamental understanding of the ignition of liquid fuel sprays is essential. To this end, a systematic program to study the ignition of monodisperse fuel sprays in the so called transition region is being undertaken at Drexel University. Some experimental results of the minimum ignition energy of n-heptane sprays are presented here.

The transition region is usually associated with droplets in the 10-100 μm range. The following important effects have been observed in the transition region: (1) maxima in burning velocity (Polymeropoulos and Das, 1975; Polymeropoulos, 1984; Hayashi et al., 1976); (2) extension of lean flammability limits (Burgoyne and Cohen, 1954; Hayashi and Kumagi, 1974); (3) minima in ignition energy requirements (Rao and Lefebvre, 1973; Ballal and Lefebvre, 1978; Chan and Polymeropoulos, 1981; Chan, 1982); and (4) minima in NO_x formation (Nizami and Cernansky, 1979; Nizami et al., 1982; Sarv et al., 1983; Cernansky and Sarv, 1983). Therefore, combustion in the transition region is an attractive design goal for practical combustors.

Previous research (e.g., Burgoyne and Cohen, 1954; Cernansky and Sarv, 1983) has shown that in the transition region, control of the combustion process is transformed from diffusive to premixed domination. It has been suggested that this transformation in controlling mechanism is responsible for the observed transition region phenomena. More specifically, these phenomena

are associated with the complex interactions between droplets in the size and number density range where the presence of neighboring droplets can significantly affect the evaporative and combustion environment of the fuel spray. Overall, the combustion behavior is affected by the relative fraction of fuel initially in a prevaporized and premixed state, the average interdroplet spacing, and the fuel properties. Although considerable research has been and is being undertaken in this area by a number of investigators (e.g., Tal et al., 1983; Sirignano, 1984; Sirignano and Sommer, 1984; Bellan and Cuffel, 1983; Labowsky, 1976, 1980; Marberry et al., 1984; Ray and Davis, 1980, 1981; Peters et al., 1984; and others), a consolidated picture of these transition region phenomena and their mechanisms is not yet available. This is due in part to the very different aerosol generating techniques (generally poorly controlled polydisperse sprays), limited and dissimilar operating ranges (e.g., equivalence ratio), different combustion systems, etc. used by the various experimental investigators.

The situation with regard to ignition energy and ignition phenomena in the transition region is not much better. Again, because of the complex configuration and geometry of sprays (even monodisperse sprays), adequate predictions of droplet interaction effects on spray ignition are not available. It remains difficult to directly compare detailed model predictions with experimental data because there are little data from spray configurations which correspond to those that have been modeled. Furthermore, much of the experimental ignition data to date has been for polydisperse sprays where the drop sizes which may control the evaporation and interactions are not well characterized. Where monodisperse sprays have been used, there has generally been poor control of other variables. More specifically, Rao and Lefebvre's (1973) and Ballal and Lefebvre's (1978, 1979) important

ignition studies were for polydisperse sprays with droplets in the diameter range of 30 to 120 microns. Thus, it is not possible to isolate the precise droplet diameter at which the ignition energy requirement is really minimum. Also, Chan and Polymeropoulos (1981) used Burgoyne and Cohen's (1954) aerosol generator and, hence, could only produce droplets over a relatively narrow range of droplet diameters without changing equivalence ratio. Thus, they could not perform their experiments over the entire transition range of droplet diameters and equivalence ratios. The reported data is only for a droplet diameter range of 10 and 30 μm and equivalance ratios from 0.39 to 1.0. Further, recent data have raised questions about the results of Chan and Polymeropoulos (Polymeropoulos, 1985). For these reasons, a complete and comprehensive picture of ignition energy variation in the transition region is not available.

The data which are presented here are some results obtained with a spray facility which overcomes many of the above problems and limitations. The major components of the facility include: a Berglund-Liu droplet generator which supplies the monodisperse fuel spray to a combustion tunnel; a spark ignition system with the capability of independently varying the spark duration, energy, and gap; and a data acquisition system consisting of a Norland Prowler two-channel digital oscilloscope, capable of data acquistion at rates up to 20 million samples per second. This facility has been used to accurately determine the minimum energy required to ignite n-heptane sprays in the transition region.

II. EXPERIMENTAL APPARATUS

1. SPRAY BURNER

A Berglund-Liu vibrating orifice aerosol generator was used to supply a well-defined and characterized spray of fuel droplets for ignition studies. In this system, droplet size, number density, flow velocities, stoichiometry, fuel type and properties, and extent of prevaporization can be independently varied and their effects isolated and studied. It can be shown that for a given fuel flow rate and droplet diameter in air, the average interdroplet spacing is determined uniquely by the equivalence ratio. However, this can be controlled and modified by employing diluents or oxygen enrichment. Nonetheless, for the present experiments, only initial droplet size, equivalence ratio and spray velocity were varied. The fuel used was n-heptane. The fuel and air were at 20°C and there was no appreciable prevaporization prior to ignition.

The aerosol generator provides a spray whose droplet diameters can be routinely varied between 10-100 μm with a standard deviation of less than 1 percent of the mean for monodisperse sprays. After generation, the droplets are subjected to a flow of dispersion air to prevent coagulation. The aerosol then passes through a flow reducing section where dilution air is added to achieve the desired stoichiometry. Both the dispersion and dilution air flows are adjusted and monitored by electronic flow controllers. Thus, the equivalence ratio can be varied over the entire range of flammability.

The basic system is the same as that previously used by Nizami and Cernansky (1978, 1979), Nizami et al. (1982), Sarv et al., (1983) and Cernansky and Sarv (1983), with some modifications. In particular, a downward flowing spray orientation has been chosen in order to prevent accumulation of fuel droplets in the test section. This provides better uniformity of the

spray, smaller differences between droplet and air flow velocities, and a margin of safety by preventing fuel accumulation within the burner. Also, the test section has been fitted with a set of ignition electrodes, which can be adjusted for gap spacing, position in the fuel spray, geometry, etc. Further, the design of the flow reducing section has been changed in order to provide flow velocities which always exceed the flame speed, thereby preventing flashback. Special consideration was given to maintaining uniform flow as well, since a screen flameholder, such as that used in previous NO_x emission experiments, is not appropriate for use in the present ignition experiments. Tests have shown that the present spray apparatus achieves a uniform aerosol flow with virtually no fuel droplet accumulation in the test section. A schematic of the modified spray burner facility is presented in Figure 1.

2. IGNITION SYSTEM

In order to determine the minimum energy needed to ignite a combustible mixture, a capacitive discharge spark ignition system has been developed. Briefly, the ignition system follows the design of Peters (1981) with a few additional features added for improved safety and convenience of operation. A schematic of the system is shown in Figure 2. The spark energy and duration can be independently controlled by varying the charging voltage, the capacitance, or the resistance of the circuit. (Switches are used to connect or disconnect capacitors or resistors from the circuit.) The capacitors are charged to approximately 20 KV using a high voltage source by closing switch S_c; after charging and before ignition, the voltage source is disconnected from the circuit by opening S_c. The grounding switch, S_g, and the discharge switch, S_d, which are open while charging the capacitors, are then closed. When this happens, a large voltage difference forms across the electrodes and a spark is generated.

To measure the spark energy, two high voltage probes are connected across the resistor bank and the voltage traces of the spark are recorded on a Norland two-channel digital oscilloscope. The probe locations are indicated in Figure 2. Typical voltage traces obtained from the two probes are shown in Figure 3. The voltage difference across the resistor bank divided by the equivalent resistance of the resistor bank gives the current, I. (The voltage measurements are made relative to ground.) The energy of the spark, E, is determined from $E = \int_0^t V(\tau)I(\tau)d\tau$ where V is the measured voltage drop across the electrodes during the spark, as measured by probe 2, and τ is time. The upper limit of the integration, t, is the spark duration. This was taken equal to four times the time constant of the current trace. The waveform processing capability of the digital oscilloscope readily provides evaluation of the above integration.

It should be noted that care has been taken to provide short cable lengths in order to minimize ground loops and any stray inductance or capacitance. This was found to be important by Ballal and Lefebvre (1975) and it did provide improved energy measurements in this study.

As noted above, stainless steel electrodes were used to deliver the ignition spark discharge. The electrodes were mounted in the test section with their main axes normal to the spray direction. This configuration has been shown by Ballal and Lefebvre (1975) to produce more consistent sparks than electrodes mounted with their axes parallel to the flow. The electrodes were mounted on a micrometer traversing assembly which was used to adjust the spark gap, as shown in Figure 1. The electrodes were 5 mm diameter stainless steel rods, with the spark-producing ends machined to 1 mm diameter, and 6 mm length. The high-voltage side electrode tip was pointed, while the ground-side tip was flat, as shown in Figure 4.

III. IGNITION ENERGY MEASUREMENTS

1. SPARK DURATION OPTIMIZATION

The effect of spark duration on ignition energy was tested initially. With a constant spark gap of 2.0 mm, ignition frequency measurements were made at two equivalence ratios (0.5 and 1.0) and two initial droplet diameters (28 and 68 μm) for each of five durations from 15 to 150 μs. For a given spark duration, capacitance and resistance values were varied to produce sparks of three to five different energies, ranging from 0.6 to 10 mJ. One hundred sparks were delivered to the fuel spray at each spark energy and duration, and frequency of ignition was determined by visual observation. The criteria for ignition was the observation of a visible, propagating flame. Spark energy and duration were measured every fifth spark and an average spark energy was determined with a standard deviation of 20 percent of the mean.

The results showed little effect of duration on ignition energy, as seen in Figure 5. These results are in basic agreement with the data of Ballal and Lefebvre (1975), who reported very little effect of spark duration on ignition energies of propane/air mixtures for durations in the 40 to 100 μs range. However, Rao and Lefebvre (1976) reported a greater effect of spark duration on ignition energies of kerosene/air mixtures with droplets in the 52 to 72 μm Sauter mean diameter (SMD) range. By varying the duration from 30 to 100 μs they saw changes of up to 100 percent in minimum ignition energies for kerosene fuel sprays.

Based on the above results, spark durations in the 70 to 80 μs range were chosen for the present study. The range of variability in spark duration for a given setting of the ignition system was about ±8 percent of the mean.

2. GAP OPTIMIZATION

The electrode gap spacing was optimized for n-heptane sprays at equivalence ratios of 0.6, 0.8 and 1.0, and each initial droplet diameter

studied. At a given condition, the optimum gap was determined by varying the electrode spacing from 0.5 to 5.0 mm in 0.5 mm steps while keeping the spark energy constant, and observing which gap gave the maximum ignition frequency for fifty sparks. A representative graph of the effect of spark gap on frequency of ignition is shown in Figure 6. These tests showed the optimum gap was 3.0 mm for all cases studied except for the 30 μm droplets at $\phi = 0.6$. In this case the optimum spark gap was 3.5 mm.

3. MINIMUM IGNITION ENERGIES

In order to determine the effect of droplet size and equivalence ratio on the minimum energy required to ignite a n-heptane spray, the criteria for that minimum had to be established. The ignition phenomenon is such that a sharp division does not exist between energies which are sufficient for ignition and those which are not. Instead, there is a range of energies for which ignition becomes more likely as the energy increases, and one can speak of the probability or frequency of ignition for a given spark energy. Some researchers have designated the energy at which ignition is observed 50 percent of the time as the minimum ignition energy. Others have used either the 90 percent value, the 100 percent value, or have not stated their criteria. For the sake of providing data which is on the conservative side, it was decided to denote the energy at which ignition is observed 90 percent of the time as the minimum ignition energy.

The minimum ignition energy was determined for a fuel spray of given initial droplet diameter and equivalence ratio in the following manner. Ignition frequency observations were made for 3 to 5 sets of 50 sparks each at 2 or 3 different spark energies. The spark energies and, hence, the capacitance and resistance settings of the ignition system were selected such that the ignition frequency values fell between 60 and 100 percent. The spark

energy was measured for every fifth or 10 of the fifty sparks; the standard deviation of these measurements was typically 20 percent of the mean energy. These ignition frequencies and their corresponding spark energies were then plotted. Representative data is shown in Figure 7, which is for 60 μm droplet diameter sprays at equivalence ratios of 0.6, 0.8 and 1.0. Each point in Figure 7 represents one set of 50 sparks. The straight lines in Figure 7 were fit to the data by a least-squares method, and the minimum ignition energy (90 percent ignition frequency energy) was determined from these lines. This figure clearly shows that the ignitability of the spray increases as the equivalence ratio increases from 0.6 to 1.0.

From data such as that presented in Figure 7, the minimum ignition energy was determined for droplet sizes of 40, 50, 60, and 70 μm and equivalence ratios of 0.6, 0.8, and 1.0. Figure 8 shows the effect of varying droplet diameter on the minimum ignition energy for the three equivalence ratios which were investigated. As noted, the data points on this figure represent the intersection of the straight-line-fit and the 90 percent ignition frequency on Figure 7 and similar figures. The error bars on the figure represent the uncertainty in the determination of the minimum ignition energy (90 percent ignition frequency). This was determined from the uncertainties in the spark energy and ignition frequency which were, in turn, taken as the 90 percent confidence levels for those values. The uncertainty in the minimum ignition energy was thus determined to be 12 percent.

As seen in Figure 8, the minimum ignition energy increased for all equivalence ratios as the initial droplet diameter was raised from 40 to 50 μm. Decreasing ignition energies were observed at all equivalence ratios as the droplet diameter was increased from 50 to 60 μm. From 60 to 70 μm the minimum ignition energy increased at $\phi = 0.6$, remained level at $\phi = 0.8$, and

decreased slightly at ϕ = 1.0. This indicates the possibility of a local minimum in ignition energies for monodisperse n-heptane sprays, located at about 60 μm initial droplet diameter for ϕ = 0.6 and shifting towards higher droplet sizes with increasing equivalence ratio. Again, this figure illustrates that the ignitability of these sprays is enhanced as the equivalence ratio is increased from 0.6 to 1.0.

The 40 to 70 μm sprays used for the data above were all generated with a fuel flow rate of 0.18 cc/min, which resulted in droplet velocities of 34, 26 and 20 cm/sec for equivalence ratios of 0.6, 0.8 and 1.0 respectively. Additional measurements were made on 60 and 70 μm sprays with a higher fuel flow rate of 0.24 cc/min without changing any other parameters. This resulted in a 28 percent increase in spray velocities, to 45, 34 and 27 cm/sec respectively. Figures 9 and 10 show a 20 to 25 percent increase in minimum ignition energies observed for the 60 and 70 micron sprays at the higher spray velocities.

IV. CONCLUSIONS

A spray combustion facility has been developed to study the ignition characteristics of monodisperse sprays in the transition region. Procedures for spark duration and gap spacing optimization have been developed. The system has been used to determine the minimum ignition energy of some monodisperse n-heptane sprays. In particular, the effects of initial droplet diameter and equivalence ratio were considered. The data shows that a local minimum of the minimum ignition energy exists. The droplet diameter at which this minimum occurs increases with increasing equivalence ratio. Flow velocity studies were performed which confirmed the expected result of increasing minimum ignition energies for increasing spray velocities.

ACKNOWLEDGEMENTS

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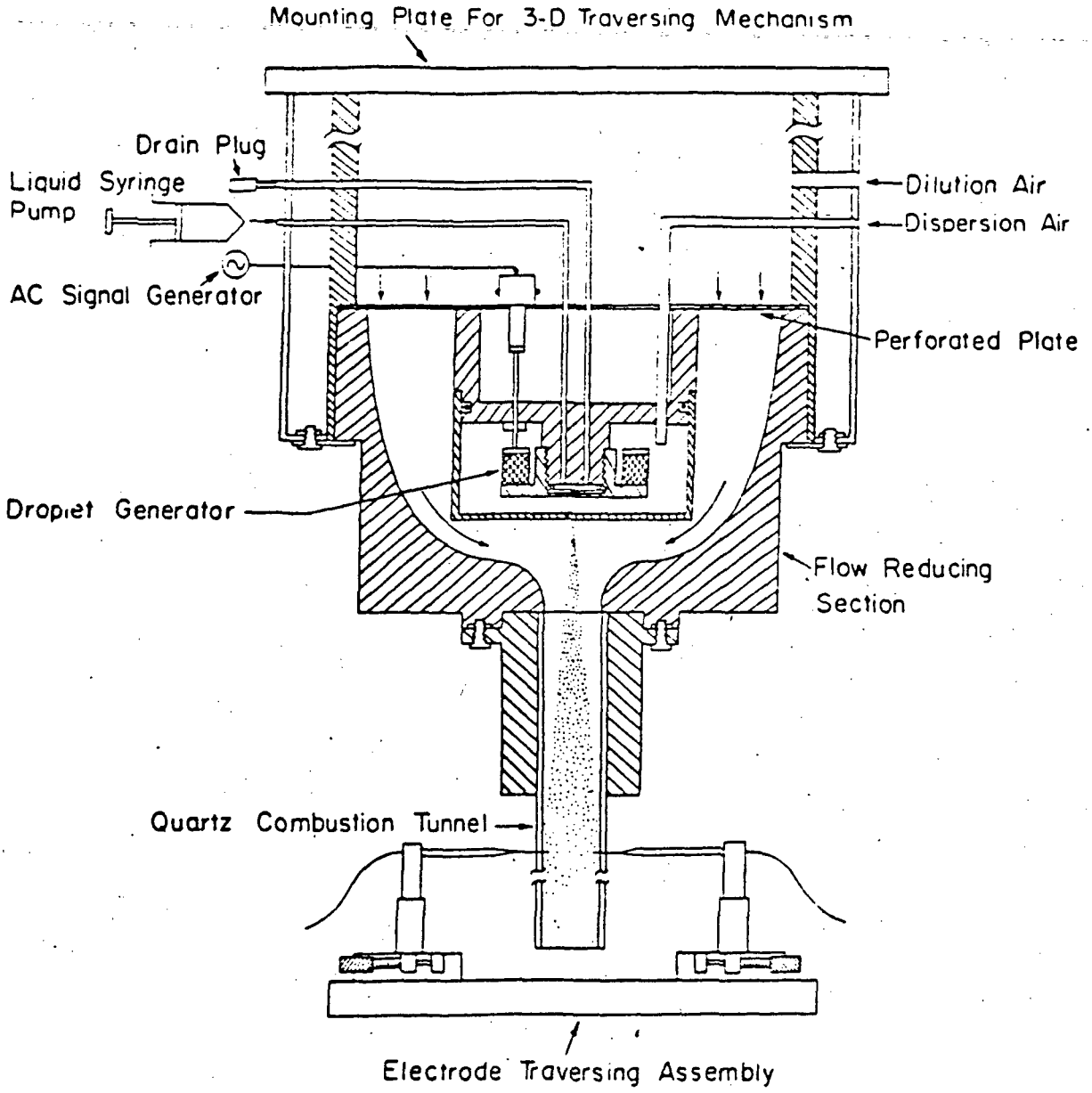

Figure I. Schematic of the Spray Burner Facility

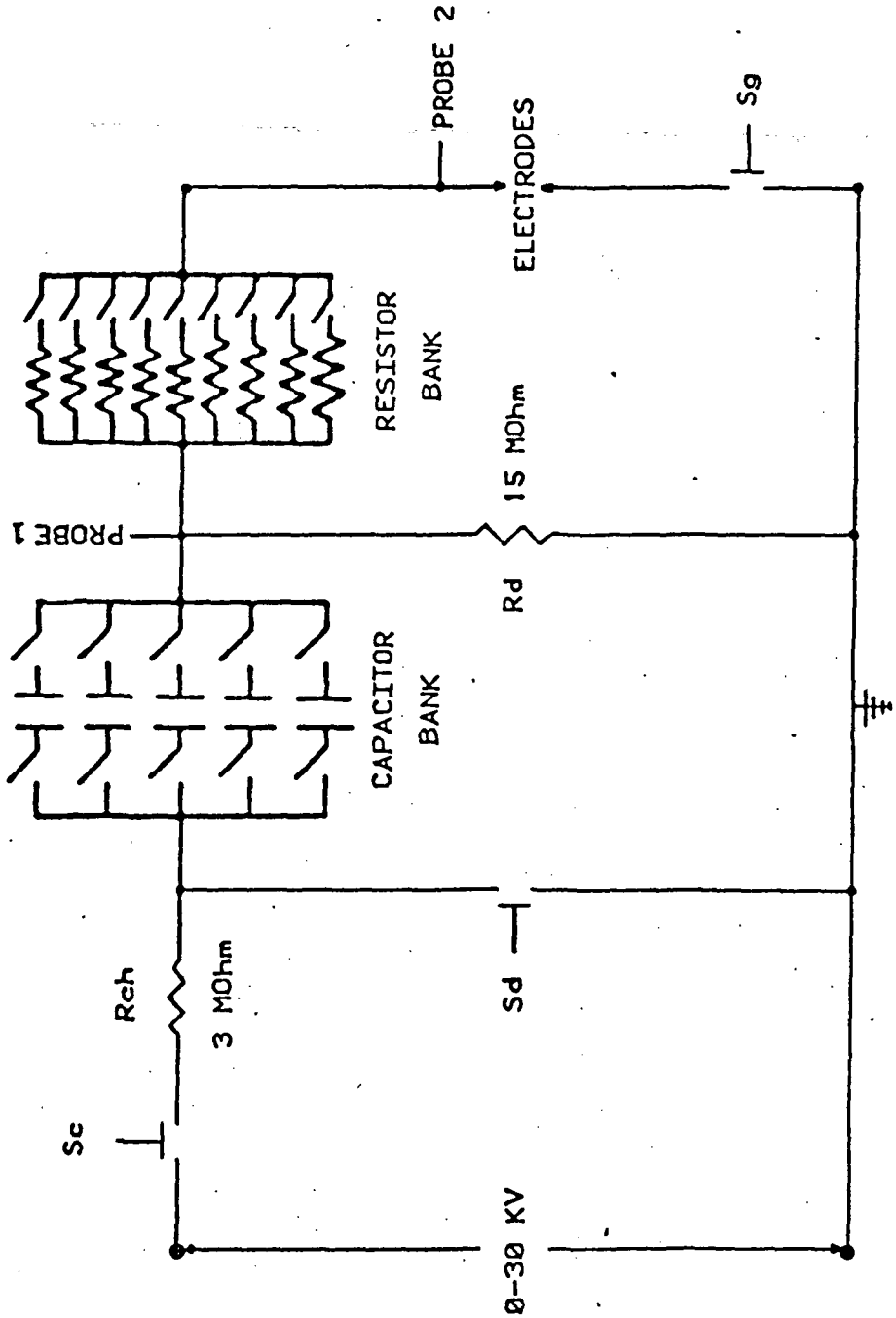

Figure 2. Schematic of the Spark Ignition System.

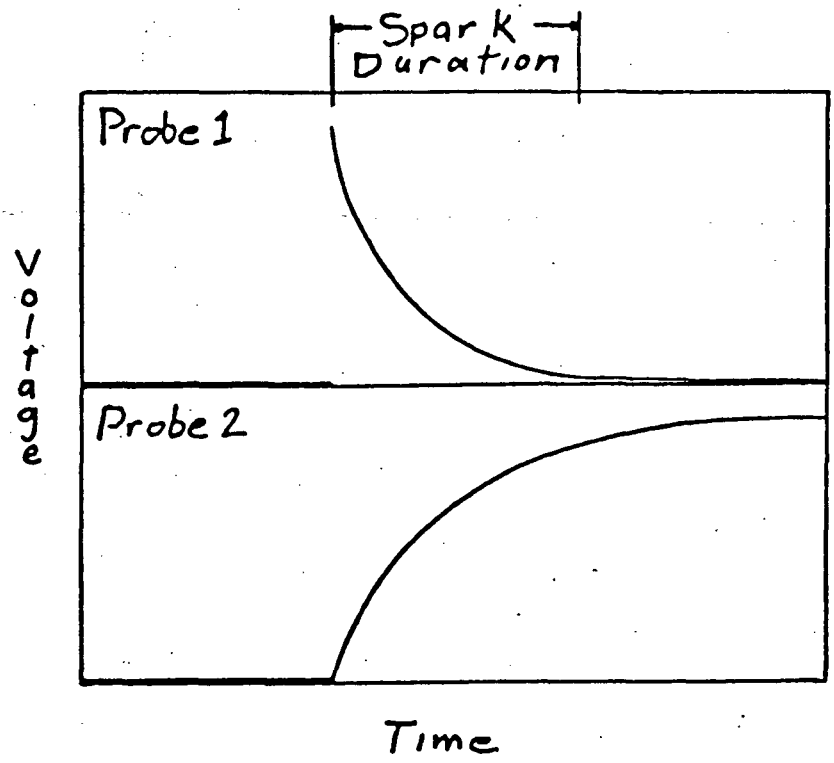

Figure 3. Typical Traces of Voltages Measured by Probes 1 and 2.

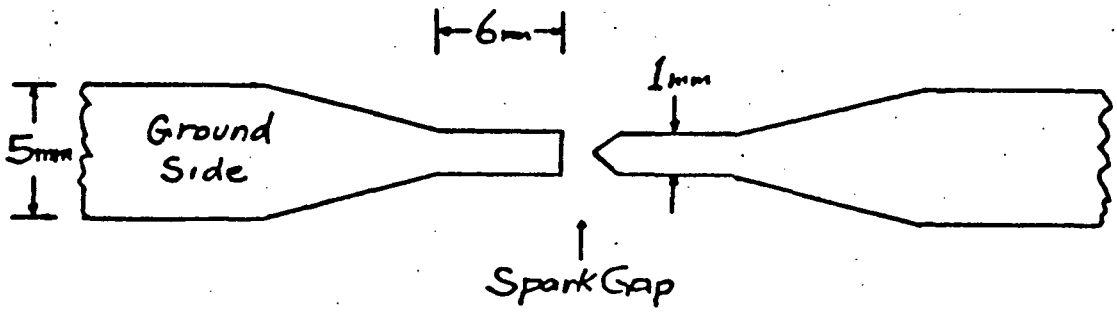

Figure 4. Design of Electrode Tips.

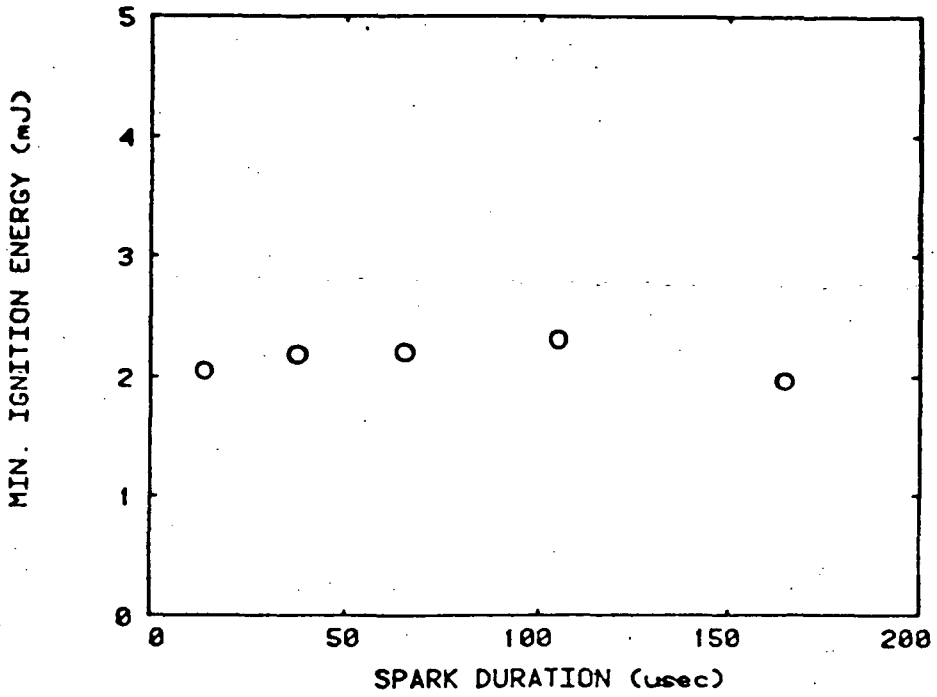

Figure 5. Effect of Spark Duration on the Energy at which 90% Frequency of Ignition is Achieved for: N-Heptane Sprays; D_o = 68 μm; ϕ = 1.0; Spark Gap = 2.0 mm.

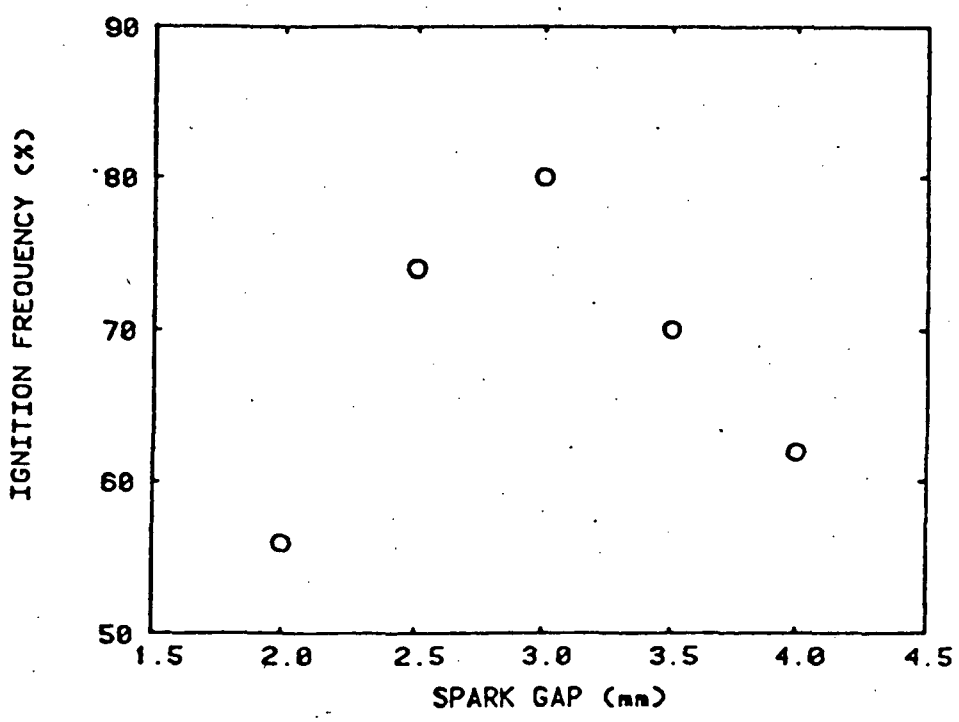

Figure 6. Effect of Spark Gap on the Frequency of Ignition for N-Heptane Sprays: D_o = 70 μm; ϕ = 1.0; Spark Duration = 76 μs; Spark Energy = 0.8 mJ.

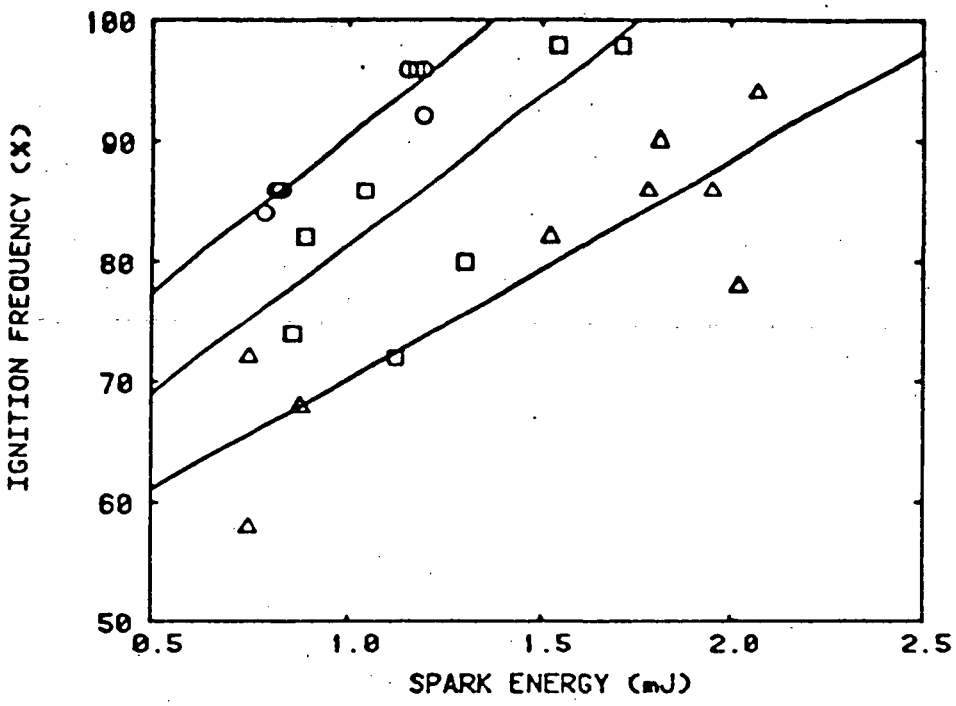

Figure 7. Effect of Equivalence Ratio, ϕ, and Spark Energy on the Frequency of Ignition of N-Heptane Sprays: D_o = 60 μm; Spark gap = 3.0 mm; Spark duration = 77 μsec. ○ - ϕ = 1.0; □ - ϕ = 0.8; Δ - ϕ = 0.6.

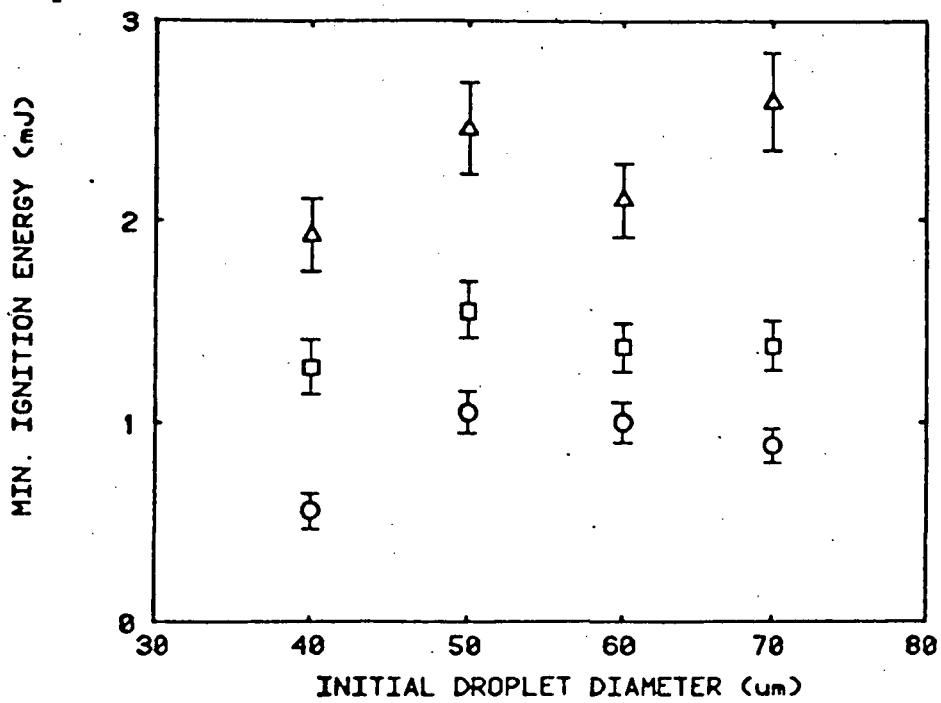

Figure 8. Effect of Initial Droplet Diameter and Equivalence Ratio, ϕ, on the Minimum Ignition Energy of N-Heptane Sprays. Spark gap = 3.0 mm; Spark duration = 77 μsec. ○ - ϕ = 1.0; □ - ϕ = 0.8; Δ - ϕ = 0.6.

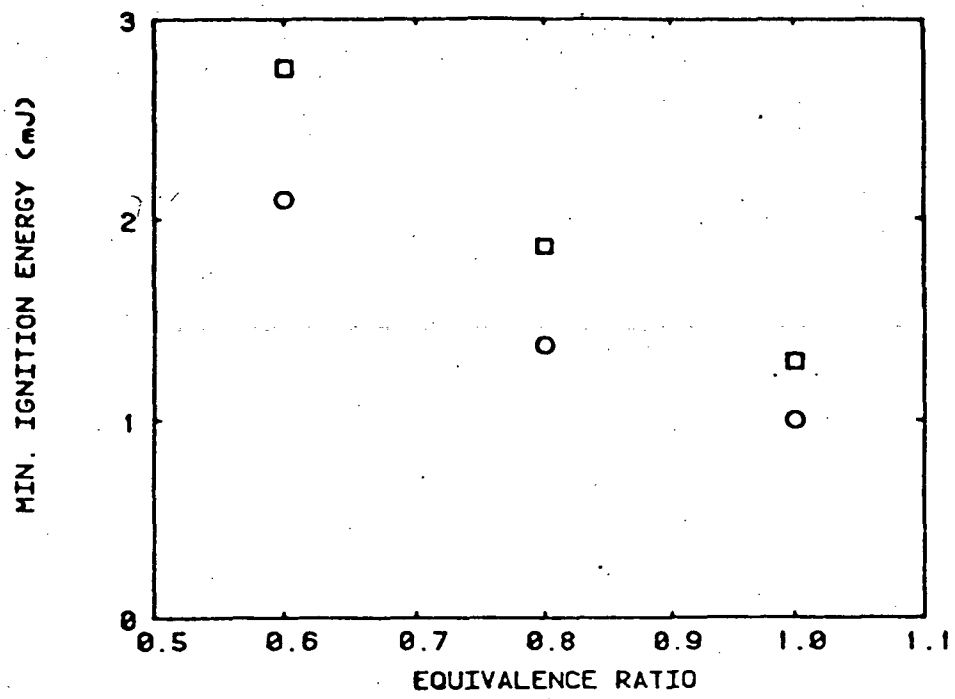

Figure 9. Effect of Fuel Flow Rate and Equivalence Ratio, ϕ, on the Minimum Ignition Energy of 60 um N-Heptane Sprays: Spark gap = 3.0 mm; Spark duration = 77 usec; Fuel flow = ○ - 0.18 cc/min, □ - 0.24 cc/min.

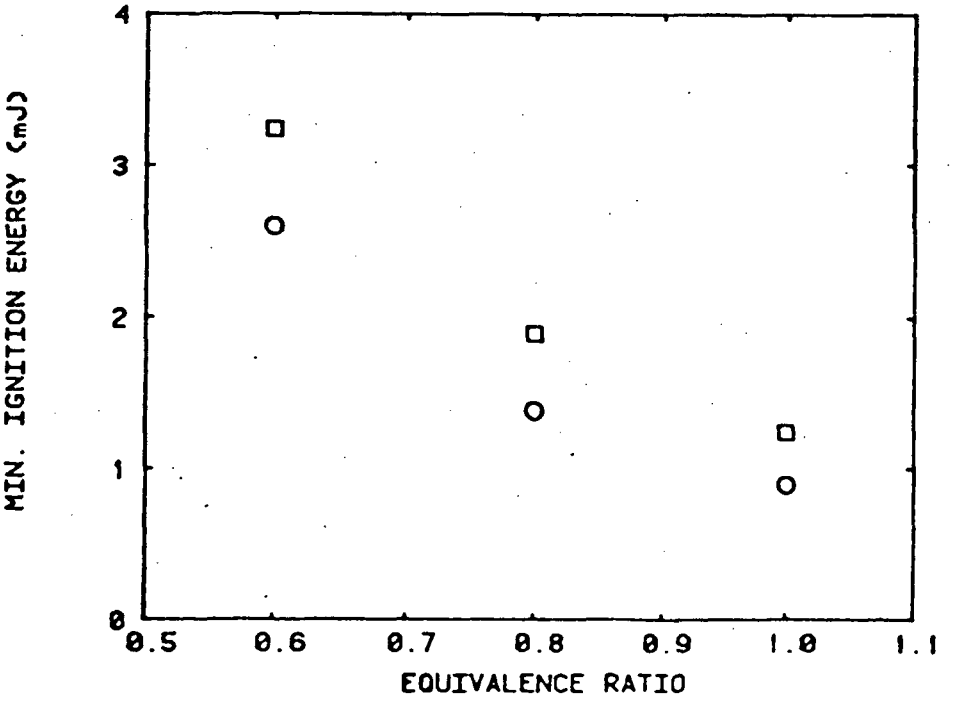

Figure 10. Effect of Fuel Flow Rate and Equivalence Ratio, ϕ, on the Minimum Ignition Energy of 70 um N-Heptane Sprays: Spark gap = 3.0 mm; Spark duration = 77 usec; Fuel flow = ○ - 0.18 cc/min, □ - 0.24 cc/min.