SPARK IGNITED TURBULENT FLAME KERNEL GROWTH

FINAL REPORT

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Date Published - June 1995

PREPARED FOR THE UNITED STATES
DEPARTMENT OF ENERGY

Under Contract No. DE-FG04-90AL62353

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ABSTRACT

An experimental study of the effects of spark power and of incomplete fuel-air mixing on spark-ignited flame kernel growth was conducted in turbulent propane-air mixtures at 1 atm, 300K conditions.

The results showed that increased spark power resulted in an increased growth rate, where the effect of short duration breakdown sparks was found to persist for times of the order of milliseconds. The effectiveness of increased spark power was found to be less at high turbulence and high dilution conditions. Increased spark power had a greater effect on the 0-5 mm burn time than on the 5-13 mm burn time, in part because of the effect of breakdown energy on the initial size of the flame kernel. And finally, when spark power was increased by shortening the spark duration while keeping the effective energy the same there was a significant increase in the misfire rate, however when the spark power was further increased by increasing the breakdown energy the misfire rate dropped to zero.

The results also showed that fluctuations in local mixture strength due to incomplete fuel-air mixing cause the flame kernel surface to become wrinkled and distorted; and that the amount of wrinkling increases as the degree of incomplete fuel-air mixing increases. Incomplete fuel-air mixing was also found to result in a significant increase in "cyclic" variations in the flame kernel growth. The average flame kernel growth rates for the premixed and the incompletely mixed cases were found to be within the experimental uncertainty except for the 33%-RMS-fluctuation case where the growth rate was significantly lower. The premixed and 6%-RMS-fluctuation cases had a 0% misfire rate. The misfire rates were 1% and 2% for the 13%-RMS-fluctuation and 24%-RMS-fluctuation cases, respectively; however, it drastically increased to 23% in the 33%-RMS-fluctuation case.

EXPERIMENT FOR STUDY OF THE EFFECT OF SPARK POWER

- The turbulent flow system used to study the effect of spark power on spark-ignited flame kernel growth is shown schematically in Figure 1. It consists of three separate gas delivery systems for air, propane, and nitrogen which are used to achieve the desired fuel/air equivalence ratio and dilution level. Turbulence is generated by forcing the flow

Figure 1. Turbulent flow system.

through narrow slots (0.32 mm wide by 50.8 mm long), as illustrated in Figure 1. This produces large vortical structures which then breakup in a converging section before entering the test section, resulting in very high levels of turbulence. The turbulence conditions have been measured with LDV and both the mean velocity and the turbulence intensity have been found to be uniform within 10% over the test section cross-section. The test section is 12.7 mm by 50.8 mm in cross-section and 75 mm long. The wide test section walls are made of quartz to provide optical access for laser shadowgraph measurements. A non-resistive J-gap spark plug with a 1.2 mm gap is mounted in one of the narrow test section walls. The orientation of the ground

electrode plug is perpendicular to the flow to minimize the effect of the wake on the spark channel.

- Three ignition systems were used to investigate the effects of ignition spark power on flame kernel growth; a GM High Energy Ignition (HEI) system, a low power breakdown (LPBD) system and a high power breakdown (HPBD) system.

The HEI system consists of an ignition module, an ignition coil, a triggering circuit, a J-gap spark plug with 1.2 mm gap spacing (Champion Z-8), and a 12 VDC power supply.

The voltage and current characteristics of the spark produced by the HEI system were measured with a high-voltage probe (Tektronics P6015) and the current with an inductive current probe (Pearson Electronics 3464). The voltage and current signals, as well as the power and energy curves, were recorded simultaneously on a digital oscilloscope (HP 54510A). The ignition energy deposited during the ~ 100 nsec long breakdown phase was calculated directly from the measured voltage and current, i.e. $E = \int VI \, dt$, and was 0.66 mJ. The lower voltage discharge (~ 750 V, ~ 4 msec) following breakdown is known as the glow discharge phase, and most of the supplied ignition energy (~ 59.1 mJ) is deposited during this phase. The effective energy, defined as the actual energy deposited in the gas mixture, was estimated as 4.73 mJ for the glow phase and 0.62 mJ for the breakdown phase. The HEI ignition system, therefore, operates predominantly in the glow discharge mode. Based on the supplied ignition energy and total duration, the average power for the HEI spark is approximately 14 watts.

The breakdown ignition system (Figure 2) consists of a high-voltage DC power supply, a resistor, a capacitor (470 pF for the LPBD system, or 2500 pF for the HPBD system), a high-voltage vacuum switch (Jennings RGD-1), an external switch, a diode, and a J-gap spark plug with 1.2 mm gap spacing. The purpose of the diode is to prevent current oscillations when the capacitor discharges into the spark gap. The power supply charges the capacitor to a voltage of 13 KV for both the LPBD and HPBD systems. The ignition spark occurs when the external

switch is activated which causes the electromagnetic switch in the vacuum switch to disconnect the power supply from the capacitor and to connect the capacitor and spark plug. In the LPBD spark, the voltage and current rise to peak values (3.6 KV and 180 A) and decrease very rapidly in a short period (~ 100 ns). The breakdown voltage for the HPBD system was about the same as that of the LPBD system, but the peak current was much higher (~ 800 A).

Table 1. Ignition System Characteristics

Ignition system	HEI	LPBD	HPBD
Supplied ignition energy	59.8 mJ	5.7 mJ	60 mJ
Breakdown phase	0.66 mJ	5.7 mJ	60 mJ
Glow phase	59.1 mJ		
Effective ignition energy	5.35 mJ	5.36 mJ	56.4 mJ
Breakdown phase	0.62 mJ	5.36 mJ	56.4 mJ
Glow phase	4.73 mJ		
Spark duration	~ 4.2 msec	~ 100 nsec	~ 100 nsec
Avg. supplied spark power	~ 14 W	~ 57 KW	~ 560 KW

Table 1 summarizes the characteristics of the three ignition systems. The supplied ignition energy is an average value for 25 ignition events in a propane-air mixture at 300 K, 1 atm and a fuel/air equivalence ratio of 0.93. The standard deviation of the measured energy, peak voltage, peak current, and peak power was less than 5 %. The effective energy is equal to the supplied energy times the energy transfer efficiency which is 8 % for the glow discharge and 94% for the breakdown discharge. As shown in Table 1, the estimated effective energies of the HEI and the LPBD systems are about the same, but the difference in the average spark power is approximately three orders of magnitude. On the other hand, the HPBD system has about the same supplied energy as the HEI system, but its effective energy is about ten times that of the HEI and LPBD sparks and its average spark power is approximately four orders of magnitude greater than that of the HEI spark.

Figure 2. Schematic diagram of the LPBD and HPBD system.

- High speed laser shadowgraphy was used to record the temporal evolution of the spark-ignited flame kernels. The shadowgraph images were recorded using a high speed video camera system. Measurements were made at 4000 frames per second (fps) for all three ignition systems, which corresponds to $250 \mu\text{s}$ between frames. In the case of the HPBD system, measurements were also made at 12000 fps to better resolve the early flame kernel growth. At each operating condition, flame kernel images of ten separate ignition events were recorded.
- Table 2 shows the test conditions used to study the effect of spark power. A propane-air mixture with a fuel/air equivalence ratio of 0.93 was supplied to the test section at a flow rate corresponding to a nominal 1 m/sec mean flow velocity in the test section. Nitrogen was used as a diluent to simulate the effect of residual gas under idle operating conditions. Dilution levels of 8% and 14% were used, where dilution level is defined as the nitrogen volume flow rate divided by the air volume flow rate. The pressure and temperature were 1 atm and 300 K, respectively. Two turbulence conditions were used to study the effects of turbulence on flame kernel growth. The mean velocity and turbulence intensity were measured with laser Doppler

velocimetry. The average mean velocity and turbulence intensity were 1.25 and 0.33 m/sec, respectively, in the low turbulence case, and 1.04 and 0.88 m/sec, respectively, in the high turbulence case. Relative to the flow conditions in an engine, these turbulence levels could correspond to a ratio of turbulence intensity to mean piston speed (for a 10 cm stroke and 800 rpm) of $\sim 1/10$ and $\sim 1/3$, respectively. The integral length scale was estimated to be 4 mm, based on two-point spatial correlation measurements made in a nearly identical flow system.

Table 2. Test Conditions

Fuel	Propane ($\phi = 0.93$, premixed)	
Diluent	Nitrogen (0, 8 and 14% premixed)	
Pressure	1 atm	
Temperature	300 K	
Flow Characteristics	Low Turbulence	High Turbulence
Mean Velocity	1.25 m/sec	1.04 m/sec
Turbulence Intensity	0.33 m/sec	.088 m/sec
Relative Turbulence Intensity	27%	85%
Integral length scale	~ 4 mm	~ 4 mm

- The flame kernel images were projected onto a digitizing table. The flame kernel boundary was digitized by manually tracing the flame boundary, and the projected area enclosed by the flame kernel boundary was calculated. An equivalent flame kernel radius was defined as that of a semi-circle whose area is the same as the projected area of the flame kernel. This digitizing process was repeated for 10 separate ignition events at each operating condition, producing ten individual equivalent radius-versus-time curves. These ten cases were averaged to yield an average equivalent radius and its standard deviation. The average growth rate was obtained by taking a derivative of the average equivalent radius-versus-time curve.

The average growth rate was compared with the laminar growth rate of the flame kernel at each test condition, which is defined as

$$\left[\frac{dr}{dt}\right]_{lam} = \frac{\rho_u}{\rho_b} S_L \quad (1)$$

where ρ_u and ρ_b are unburned and burned gas density, respectively, and S_L is the laminar flame speed. The burned gas density was calculated using the NASA equilibrium code. The unburned gas density was determined from the ideal gas law. The laminar flame speed for propane-air mixtures as a function of the diluent mass fraction was obtained from

$$S_L = (1 - 3.0f) S_L(0) \quad (2)$$

where $S_L(0)$ is the unstretched, adiabatic laminar flame speed without dilution and f is the diluent mass fraction. The unstretched, adiabatic laminar flame speed (in cm/sec) for propane-air mixtures without dilution as a function of fuel/air equivalence ratio at a temperature of 298 K and pressure of 1 atm is given by

$$S_L(0) = 38.31 + 24.84(\phi - 1) - 153(\phi - 1)^2 \quad (3)$$

where ϕ denotes the fuel/air equivalence ratio.

EXPERIMENT FOR STUDY OF THE EFFECT OF INCOMPLETE FUEL-AIR MIXING

The turbulent flow system used to study the effect of incomplete fuel-air mixing on spark-ignited flame kernel growth is similar to the one shown in Figure 1 and described previously. The mean velocity and turbulence intensity were measured with LDV at nine locations over the width of the test section, at the same height as the spark electrode. The mean velocity and turbulence intensity averaged over the nine locations were 1.16 m/sec and 0.25 m/sec, respectively. Relative to the flow conditions in an engine, the turbulence level corresponds to a ratio of turbulence intensity to mean piston speed (for a 10 cm stroke and 800 rpm) of $\sim 1/10$.

The integral length scale was estimated to be 4 mm, based on two-point spatial correlation measurements.

3. Test section for generating incomplete fuel-air mixing.

Incomplete fuel-air mixing is achieved by introducing the fuel (propane) at two different locations. The primary location is about 160 flow tube diameters upstream of the test section which insures complete fuel-air mixing. The secondary location is approximately 1 cm upstream of the test section where the fuel is introduced through four fuel tubes, as shown in Fig. 3. By varying the fraction of fuel added at these two locations, the degree of incomplete fuel-air mixing in the test section can be changed. In this study, a (100%) premixed case and four incompletely mixed cases were established while the overall fuel-to-air (fuel/air) equivalence ratio was 1.0. These four cases are referred to as the 75% premixed, 50% premixed, 25% premixed, and 0% premixed cases. For example, the 75% premixed case is obtained by adding 75% of the fuel at the primary location and the 25% at the secondary location. By selecting the size of the fuel tubes so that the mean gas velocity of the secondary fuel jets matches the mean velocity of the primary flow, the secondary fuel was introduced without appreciably changing the turbulence properties of the primary flow. This was confirmed by making LDV measurements with and without the secondary fuel flow while maintaining the same flow rate through the test section.

- The degree of fuel-air mixing was characterized using an NO_2 -based LIF technique. This technique involves replacing the fuel with an equivalent volume flow rate of nitrogen which is

doped with 6500 ppm of NO_2 . The 488 nm output of an argon-ion laser was used to excite the NO_2 . The fluorescence signal was collected at 90 degrees and detected with a photomultiplier tube. The signal from the PMT was monitored and recorded by a digital oscilloscope and a computer-based A/D system, respectively.

Measurements were made over the width of the test section at nine locations which are at the height of the spark electrode and along the centerline of the test section. The mean and RMS fluctuation in fuel/air equivalence ratio is uniformly distributed across the test section. The mean fuel/air equivalence ratios averaged over the nine locations is, of course, 1.0 for all cases. The RMS fluctuations averaged over the nine locations are 0%, 6%, 13%, 24% and 33% as the degree of incomplete fuel-air mixing varies from the 100% premixed case to the 0% premixed case.

- A General Motors High Energy Ignition (HEI) system was used as the ignition system for this study. The HEI spark supplies total ignition energy of 60 mJ in about 4 msec spark duration, however $\sim 80\%$ of the energy is delivered in the first 2 msec. The variation in measured spark energy from spark to spark was less than 5%.
- High speed laser shadowgraphy was used to record the temporal evolution of the spark-ignited flame kernels. This is the same system described previously. Measurements were made at 4000 frames per second (fps) speed which corresponds to $250 \mu\text{s}$ between frames. At each operating condition, flame kernel images of twenty separate ignition events were recorded.
- Table 3 shows the test conditions used in the study of the effects of incomplete fuel-air mixing. Stoichiometric propane-air mixtures with various degrees of incomplete fuel-air mixing were supplied to the test section at a flow rate corresponding to a nominal 1 m/sec mean flow velocity. The pressure and temperature were 1 atm and 300 K, respectively. The mean velocity and turbulence intensity were 1.16 m/sec and 0.25 m/sec, respectively. The integral length scale of the turbulent velocity fluctuations was estimated to be 4 mm. The premixed and four

incompletely mixed cases were established as test conditions. The relative RMS fluctuations in the fuel/air equivalence ratio were 0%, 6%, 13%, 24% and 33% for the 100% premixed, 75% premixed, 50% premixed, 25% premixed and 0% premixed cases, respectively.

Table 3. Test conditions for the study of the effects of incomplete fuel-air mixing

Fuel	Propane
Pressure	1 atm
Temperature	300 K
<u>Flow Characteristics</u>	
Mean Velocity	1.16 m/sec
Turbulence Intensity	0.25 m/sec
Relative Turbulence Intensity	22%
Integral Length Scale	~ 4 mm
<u>Fuel-Air Mixedness</u>	<u>RMS Fluctuation</u>
100% premixed case	0%
75% premixed case	6%
50% premixed case	13%
25% premixed case	24%
0% premixed case	33%

- The flame kernel images were analyzed using the same procedure described previously, yielding equivalent flame kernel radius-versus-time curves. This process was repeated for 20 separate ignition events at each operating condition, producing twenty individual equivalent radius-versus-time curves. These twenty cases were used to calculate an average equivalent radius and its standard deviation. The average growth rate was obtained by taking the derivative of the average equivalent radius-versus-time curve, and the average growth rate was compared with the laminar growth rate of the flame kernel at each test condition.

SUMMARY OF RESULTS

The effect of spark power on spark-ignited flame kernel growth was studied in terms of its effect on both the flame kernel growth rate and the occurrence of misfire. The specific manner in which the effect of spark power was studied was to compare a long duration, glow discharge spark to short duration, breakdown sparks. In one case (HEI and LPBD), the effective energy delivered to the flame kernel was the same (~ 5 mJ), but there was a factor of $\sim 10^3$ difference in spark power. In the other case (HEI and HPBD), the energy supplied by the ignition system was the same (~ 60 mJ), but there was a factor of ~ 10 difference in the effective spark energy and a factor of $\sim 10^4$ difference in spark power. The main conclusions from this study are summarized below:

1. The initial size and thermo-chemical energy of the flame kernel increase with increasing breakdown energy.
2. The increased thermo-chemical energy of the flame kernel caused by increased breakdown energy appears to enhance the flame kernel growth rate well beyond the duration of the breakdown spark, i.e., for times of the order of milliseconds.
3. Not only does the breakdown mode of ignition result in a higher percentage of the energy supplied by the ignition system actually being delivered to the flame kernel, but that energy has a greater effect on the flame kernel growth rate. In other words, a short duration breakdown spark produces a faster growing flame kernel than a long duration spark of equivalent effective energy.
4. Neither turbulence nor dilution affect the initial flame kernel size, i.e., the size following the blast wave phase.
5. For the conditions tested, increased turbulence intensity increased the flame kernel growth rate; however, this effect became less significant as the spark power, i.e., breakdown energy,

is increased. As a consequence, the effect of increased spark power on the growth rate is less significant as the turbulence intensity is increased.

6. For the conditions tested, increased dilution reduced the flame kernel growth rate. The effect of increased spark power, i.e., breakdown energy, on the growth rate with and without dilution was relatively unchanged at the low turbulence condition; however, it was significantly reduced at the high turbulence condition.
7. Increased spark power had a significantly larger effect on the 0-5 mm burn time than the 5-13 mm burn time. This was particularly true for the HPBD system and under low turbulence, high dilution conditions.
8. The misfire rate increased with increasing turbulence and dilution for the HEI and LPBD systems. When the spark power was increased by changing from a long duration glow discharge (HEI) to a short duration breakdown discharge (LPBD), with equivalent effective energies, the misfire rate increased. But further increasing the spark power of the breakdown discharge (HPBD) resulted in no misfires for all of the conditions tested.

Additional details on this study of the effect of spark power can be found in SAE Paper No. 92-2168.

The effect of incomplete fuel-air mixing on spark-ignited flame kernel growth has been studied in terms of its effect on the flame kernel growth rate, the "cyclic" variation in the flame kernel growth and the misfire rate. The experiments were conducted at 1 atm, 300 K conditions in a turbulent flow system which allows for independent variation of flow field parameters and the degree of fuel-air mixing. The mean velocity and turbulence intensity were fixed at 1.16 and 0.25 m/sec, respectively. Five cases were studied; a premixed and four incompletely mixed cases with 6%, 13%, 24% and 33% RMS fluctuations in the fuel/air equivalence ratio. The overall fuel/air equivalence ratio was unity for all cases. The main conclusions from this study are

summarized below (Here, the quantitative results should be used with caution, however, due to the statistical uncertainty of the measurements):

1. The initial size of the flame kernel was not affected by the degree of incomplete fuel-air mixing.
2. The fluctuation in local mixture strength due to incomplete fuel-air mixing causes wrinkling and distortion of the flame kernel surface. As the RMS fluctuation in the fuel/air equivalence ratio increases, more wrinkles on the flame kernel surface can be found.
3. The "cyclic" variations in flame kernel growth for the incompletely mixed cases are greater than for the premixed case.
4. A strong correlation ($R(t,6) > 0.9$) between the early flame kernel growth rate and the subsequent size of the flame kernel was not achieved until after ~ 2 msec, i.e. until the completion of the spark assisted growth phase.
5. The mean growth of the flame kernel is within the experimental uncertainty for all test conditions except the 33%-RMS-fluctuation case which is significantly slower.
6. The standard deviation in flame kernel size, which is a measure of the "cyclic" variation in flame kernel growth, is small and relatively constant during the spark assisted growth phase (0-2 msec), after which it increases markedly until the flame kernel radius is ~ 20 mm. The standard deviations for the incompletely mixed cases are higher than in the premixed case, but no consistent trend was found.
7. The premixed and 6%-RMS-fluctuation cases had a 0% misfire rate. The misfire rates were 1% and 2% for the 13% and 24%-RMS-fluctuation cases, respectively; however, it rapidly increased to 23% in the 33%-RMS-fluctuation case.

Additional details on this study of the effect of incomplete fuel-air mixing on the growth of spark-ignited flame kernels can be found in SAE Paper No. 93-2715.