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The Impact of Spark Discharge Pattern on Flame Initiation in a Turbulent Lean and Dilute Mixture in a Pressurized Combustion Vessel

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ABSTRACT

An operational scheme with fuel-lean and exhaust gas dilution in spark ignited engines increases thermal efficiency and decreases NOx emission, while these operations inherently induce combustion instability and thus large cycle-to-cycle variation in engine. In order to stabilize combustion variations, the development of an advanced ignition system is becoming critical. To quantify the impact of spark-ignition discharge, ignitability tests were conducted in an optically accessible combustion vessel to characterize the flame kernel development of lean methane-air mixture with CO_2 simulating exhaust diluent. A shrouded fan was used to generate turbulence in the vicinity of J-gap spark plug and a Variable Output Ignition System (VOIS) capable of producing a varied set of spark discharge patterns was developed and used as an ignition source. The main feature of the VOIS is to vary the secondary current during glow discharge including naturally decaying and truncated with multiple strikes. These discharge patterns were studied to characterize the interaction of discharge phases and initial flame formation. High-speed schlieren optical setup was employed for visualization with synchronous measurement of discharge waveforms. The results showed that multi-strike discharge was able to generate multiple flame kernels whose interactions affect flame initiation. With proper timing of each discharge event the individual kernels merge and lead to propagating flame. However, this flame initiation is highly subjected to the flow field in the vicinity of spark plug. Based on these observations, a mathematical description of the discharge timing requirements is formulated to describe the multi-kernel flame initiation under turbulence.

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INTRODUCTION

World vehicle fleet size has reached 1 billion in 2010 [1] and the rapid increase of demand will double this number within 10 years [2]. Both burdens of resources and environment concerns caused by the large number of vehicles demand cleaner and more efficient internal combustion engines for on-road vehicles. Spark ignition (SI) engines, as the most widely used power units for light-to-medium load passenger cars, have been focused on in the scope of this paper.

In spite of the high efficiency nature of Otto cycle in ideal conditions, real-world gasoline engines suffer from low efficiency due to pumping loss and lower compression ratio than compression ignition (CI) engines [3]. The load and speed control of a port fuel injection (PFI) engine is typically led by air. A throttle is used to control the amount of stoichiometric mixture into the combustion chamber and causes pressure difference between intake and exhaust, which is a source of pumping loss. The stoichiometric charge preparation and "air lead" engine control strategy are mainly responsible for the low efficiency of SI engines at part loads. It is also required by the exhaust after-treatment that the equivalence ratio needs to be kept at one (stoichiometry) to allow the catalyst to work efficiently.

Efforts have been devoted to increase SI engine efficiency under partial loads. It is desired that gasoline engines can be operated un-throttled, so that pumping loss would be reduced with similar intake and exhaust pressures [4]. Engine speed and load would be controlled by adjusting the amount of fuel provided for combustion, which would often result in lean combustion under partial loads. Among the three major exhaust emissions of CO, UHC and NO_x, CO (carbon monoxide) and UHC (unburned hydrocarbon) are less likely to form in fuel-lean combustion. Furthermore, NO_x production also decreases due to the lower flame temperature of fuel-lean mixture. NO emissions decrease to low levels for equivalence ratios of less than 0.9 [3]. In addition, exhaust gas recirculation (EGR) has been suggested to further reduce flame temperature in the combustion chamber.

However, such feasible schemes to enhance the SI engine performance would face potentially great challenge from unreliable ignition of lean and dilute fuel-air mixtures.

Misfire, which is the failure of flame propagation within an engine cycle, is harmful to the physical structure of the engine components and should be avoided. Typically it is required that the coefficient of variation (COV) of an engine's indicated mean effective pressure (IMEP) over cycles needs to be kept below a certain level (e.g. 5%) to ensure consistent combustion events in consecutive cycles [5, 6]. Under such circumstances, the lean combustion level and EGR rate are both limited for conventional SI engine configurations, which is inspiring further improvement on engine design for reliable ignition when the fuel-air charge is lean and dilute.

Generally two approaches are available to eliminate ignition instability. Stratified in-cylinder charge is regarded as one promising solution as it is generating “locally stoichiometric, globally lean” fuel concentration around the spark plug [7]. Careful design of engine geometries including cylinder head, piston top, and chamber size would be necessary. On the other hand, a pursuit of an advanced ignition system is proposed to ignite the homogeneous lean fuel-air charge. In fact, the application of a variety of discharge patterns has become a major approach for advanced ignition system development.

The term “discharge pattern” refers to the waveform shape of the discharge current. A conventional inductive coil ignition system features a natural decay type of discharge pattern which results from the secondary coil of the system [8], as can be seen in Figure 1. Manipulation of discharge pattern is achievable through either adjustment on timing, setup and configurations of a conventional system or a redesign of the spark ignition circuit.

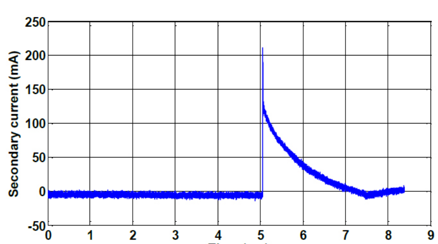
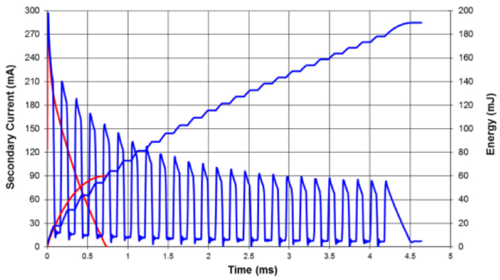


Figure 1. Natural decay type of discharge pattern from a conventional inductive coil ignition system.

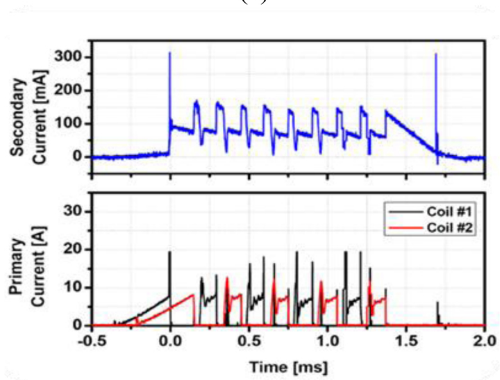
Engine tests have been conducted to estimate the effectiveness of various discharge patterns. It was founded that multi-spark discharge, continuous discharge, and repetitive pulse discharge are all beneficial under certain engine test conditions in extending the system's lean combustion and EGR limits. Multi-spark discharge can be achieved without a hardware modification of a conventional inductive coil system [6] shown in Figure 2 (a). By re-dwelling the primary coils multiple times during a single engine combustion cycle, several discharges of hundreds of microseconds are generated in a train with multiple times of breakdown into the engine charge. Similarly, a continuous discharge system is also based on conventional inductive system but has two coils attached to a single spark plug. By programming the two coils to charge and discharge in an alternative fashion, a continuous discharge through the spark plug gap is achieved with only one event of breakdown and the duration of discharge is able to last for several milliseconds [5]. The idea of conventional inductive system adjustment is to increase the energy and/or duration of discharge, especially during glow discharge mode, to ensure successful ignition as shown in Figure 2 (b). However, there are also options to use ignition circuits other than a conventional system to generate far more rapid discharges. The repetitive pulse discharge features multiple discharges of nanosecond duration at a discharge rate of 30 kHz [9, 10] shown in Figure 2 (c). This unique circuit design intends to take advantage of the breakdown discharge mode, which is most effective in terms of energy transfer, to accumulate excited radicals for easier reaction initiation.

However, it is a relatively less efficient way to understand the effectiveness of discharge patterns by monitoring the COV of engine's IMEP. Parameters such as re-dwell timing and frequency, duration of continuous discharge and number of repetitive pulses need to be determined with a better understanding on the flame kernel formation and propagation. Thus several visualization methods have been developed for direct inspection to understand flame kernel behavior under both quiescent and flow conditions.

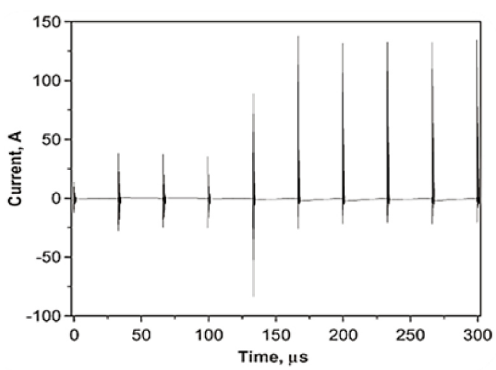
It is reported that a flame kernel is generated immediately after breakdown happens [8]. A flame kernel is a small volume of combustion products in unburned flame mixture where a thin layer of reaction occurs on the surface. Optical diagnostics including schlieren, chemiluminescence, and planar laser induced fluorescence (PLIF) have been employed for the direct observation of flame kernel behaviors [9,10,11,12].



(a)



(b)



(c)

Figure 2. Secondary current waveforms of three discharge patterns: (a) multi-spark discharge, (b) continuous discharge, and (c) repetitive pulse discharge.

Optical observation results showed that the spark ignited flame kernel often kept a spherical shape under quiescent conditions unless heat transfer occurs between the kernel and spark plug electrodes and chamber walls. It is reported that the flame kernel needs to reach a certain critical size to ensure self-sustained propagation against various types of heat losses [8, 13]. The initial flame kernel size is typically comparable with the gap size between the spark plug electrodes, thus a large spark plug gap size is relatively beneficial to ignition as long as it allows breakdown to happen. However, flame kernel behavior becomes more complicated when flow motion is involved. Well-controlled laminar vortex has been applied to study the flow effect on flame propagation [11, 12]. Vortex strength, which indicates the flow speed of the vortex, is a dominant factor in quenching a flame kernel. In addition, vortices with larger length scales would require lower vortex strengths to quench a flame kernel. Quenching of flame kernel usually occurs when the reacting front of flame kernel becomes stretched by strong flow and several local reacting fronts are propagating towards each other.

The current study is to investigate the effectiveness of various discharge patterns on spark ignited flame kernel propagation under turbulence by utilizing optical observation techniques. Experiments have been conducted in a pressurized constant volume combustion vessel. Different discharge patterns have been applied to flammable gaseous mixture filled into the vessel. With the help of optical diagnostics, the characteristics of flame kernels generated by variable discharge patterns have been described and analyzed.

EXPERIMENTAL SETUP

Experimental study has been carried out in an optically accessible constant-volume combustion vessel. Using an advanced ignition system, Variable Output Ignition System (VOIS), flame kernel development in the methane/air mixture with CO_2 as diluent is investigated through multiple optical diagnostics.

Combustion Vessel and Optical Setup

The combustion vessel (CV) at Michigan Technological University is a constant volume visualization facility capable of withstanding high pressure (up to 345 bar) and high temperature (up to 2000 K). The CV features a cubical internal chamber with a 1 L internal volume, as shown in Figure 3. The six surfaces of the cube are made as removable windows and can be configured as optically accessible sapphire windows or other test fixtures such as spark plug or fuel injector holders. A spark plug holder is mounted as the CV top window for this test setup. The eight corners of this cubic space are also made as accessible ports into the CV. For the current setting two pneumatically controlled intake and exhaust valves and a pressure transducer have taken three of these ports. In addition, this thick stainless steel body of the CV is equipped with temperature control which is able to keep the CV temperature constantly at up to 453 K.

The CV top window contains a housing to hold the spark plug as well as a shrouded fan fixture to generate flow motion in the 1 L cubic space, as shown in Figure 4. The speed and direction of rotation of the fans are configurable, allowing researchers to easily vary the fluid velocity vector at the source of ignition. The fan has a 25.4 mm outer diameter with eight straight vanes with 30-degree attack angle. Fan speed for this test was set at 8000 rpm. Once the fan is turned on, gases in the CV are directed into the shroud and ejected from a circular hole on the side of shroud. With a proper adjustment of the hole height and orientation, cross flow can be generated through the spark plug gap as the fan is turned on.

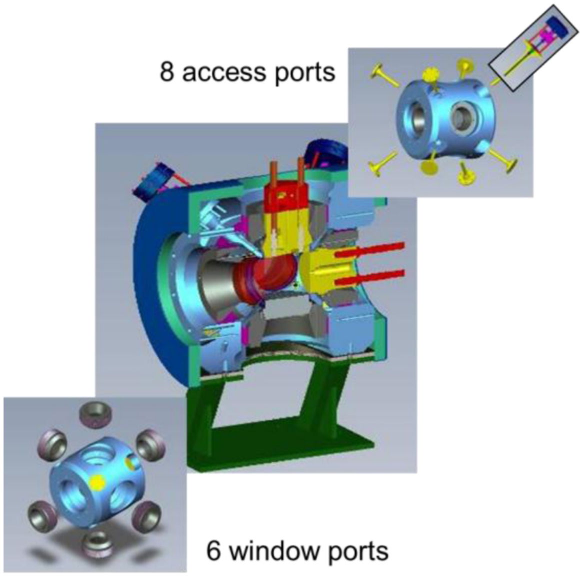


Figure 3. Constant volume combustion vessel (CV).

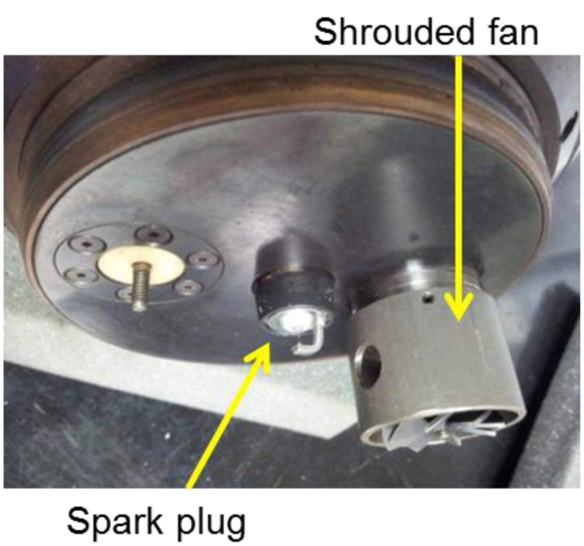


Figure 4. Top port window setup for CV, left fan has been removed. Left fan shaft is necessary to seal the CV

Schlieren and chemiluminescence imaging has been utilized for optical diagnostics as shown in Figure 5. An extended parallel beam schlieren setup utilizing two schlieren mirrors (fl = 750 mm, 152 mm diameter with f-stop of 5) and a reflector was used to visualize the high-speed spark channel and flame kernel evolution. A 65 W halogen lamp along with a 2 mm × 5 mm slit was used as a light source. By placing the light source at the focal point of the first schlieren mirror, a collimated beam is thus generated passing through the optical vessel. The collimated beam was then focused onto the second concave mirror in order to converge it onto the focusing lens just before the camera. The negative bi-convex focusing lens (fl = 100 mm) was placed in front of camera in order to match the various aperture sizes to the camera such that field of view can be readily adjustable. Particularly the view of the electrode gap can be significantly enlarged, yielding the high spatial resolution. The knife-edge was placed in a vertical position similar to the source at the point of sharp source image. The final percentage cut off was adjusted based on the optimization between the schlieren sensitivity and intensity level obtained on the camera CCD at various exposure timing. The Photron (FASTCAM SA1.1) camera is a 12 bit high speed camera with resolution of 1024 × 1024 pixels. This Photron camera is utilized with high frame rates of 25,000 to 30,000 frames per second (fps). The camera was equipped with a manual focus Nikon Nikkor lens of 50 mm focal length and maximum aperture of f-stop 1.4.

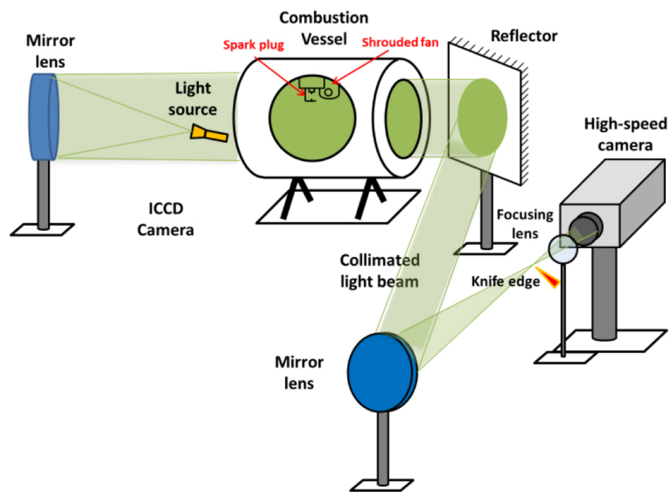


Figure 5. Optical setup for schlieren imaging.

In addition to visualization, there are two sets of high speed data acquisition (DAQ) systems available to monitor signals simultaneously with ignition event. The CV pressure is recorded at the sampling rate of 100 kHz. The pressure trace reveals the average pressure inside the vessel and can be used to calculate the transient vessel gas temperature using ideal gas laws. An oscilloscope (YOKOGAWA DL9010L) capable of 5GS/s maximum sampling rate is used to record discharge current and secondary voltage at 50 MHz.

Variable Output Ignition System (VOIS)

The VOIS has been developed by Ford Motor Company for experimental purposes. This inductive type of ignition system is intended to produce various discharge patterns, which consists of variable ignition energy, spark duration, and a number of discharge events. Unlike the traditional spark system, in which each spark plug was connected to only one set of ignition coils, the VOIS has multiple sets of ignition coils attached to a single spark plug. Diode packs are used to connect the coils.

Figure 6 shows the schematic of the VOIS circuit setup. As multiple coils are connected to a single spark plug, the VOIS system is able to deliver the spark energy from the coils simultaneously or in certain order. When the coils are discharging simultaneously, the intensity of the spark is enhanced while the spark duration can be extended if the coils are discharging alternatively. An ignition controller manipulates the charge duration of each set of coils as well thus allowing variable discharge energy and duration outputs.

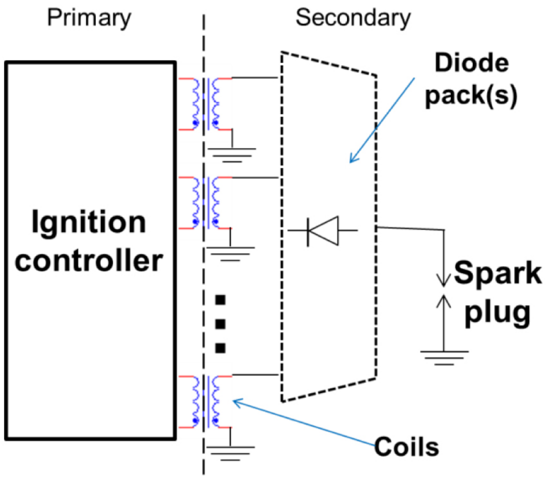


Figure 6. Schematic for circuit of variable output ignition system (VOIS).

It is also possible to manipulate the discharge waveform shape with this controller circuit. Typically, the secondary current waveform of a spark event is similar to that in Figure 1, where the spark current naturally decays with time. With a specific design of circuit, the energy associated with the end part of the natural decay current can be dissipated within the circuit components instead of through the gap, thus forming a truncated secondary current waveform. Thus, a variety of discharge patterns can be achieved by adjusting the number of discharging coils, timing and duration of each discharge.

Figure 7 shows the possible discharge patterns by combining discharges from two sets of coils. Red-dotted waveform indicates discharge from the first coil and green-solid for the second coil discharge. Continuous and discontinuous discharges are generated by varying the timing to trigger each coil. If the second coil is triggered after the spark current induced by the first discharge falls back to zero, a discontinuous discharge pattern is generated. On the other hand, if the second coil begins to discharge while the spark current of the first coil is still flowing across the spark plug gap, a continuous discharge is achieved. A similar strategy can be applied to operations with more coils. This variety of spark discharge patterns provides flexibility to spark ignition tests to be performed.

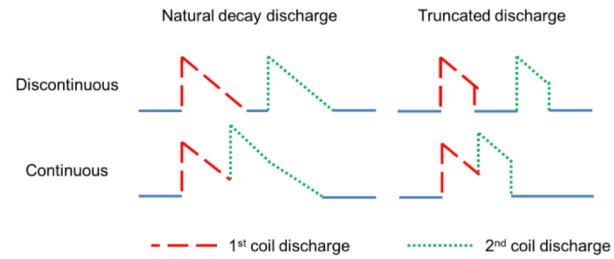


Figure 7. Variable discharge patterns available with combination of two coils discharges.

PRELIMINARY STUDY

Ignition of flammable mixture with a spark discharge is affected by a number of variables. In order to properly set the test condition, an understanding of the general trend of the effects of these variables is necessary. Preliminary study has been performed to understand basics of ignition process. A hypothesis of the ignition mechanism is proposed and test conditions were chosen to confirm the hypothesis.

Factors That Influence Ignition

The process of spark ignition typically starts with a plasma channel formed with an electrical discharge. The energetic species within the channel usually promotes a flame kernel, which will either develop to propagating flame or quench and leave most of the mixture unburned. The survival of flame kernels depends highly on the local conditions around the spark plug, including initial temperature, initial pressure of mixture, mixture composition, spark plug gap size, local flow condition as well as spark discharge patterns. A method of partial control variables was adopted to reveal effects of some of these variables.

Figure 8 shows a test result map combining effects of initial mixture pressure and spark plug gap size under quiescent condition, where mixture composition and discharge patterns are fixed. Given that breakdown occurs for all tested cases, it could be generalized that large gap size and high initial pressure are beneficial to successful ignition. It is also observed that a "gray zone" with intermittent ignition phenomenon appears between the "successful" and "failed" regions, which is an indicator of threshold effect.

Meanwhile, it is also accepted that mixture is becoming more and more difficult to ignite when the composition becomes leaner and more dilute, while the increase of discharge energy will benefit ignition.

The role of flow motion is believed to be complicated through the turbulence-chemistry interaction during the flame kernel formation. Moderate levels of turbulence will be able to wrinkle the surface of the flame kernel which increases the reacting front area potentially. However, the flow motion is also able to stretch the flame kernel, which makes the kernel more vulnerable to local extinction and would require higher discharge energy for successful ignition.

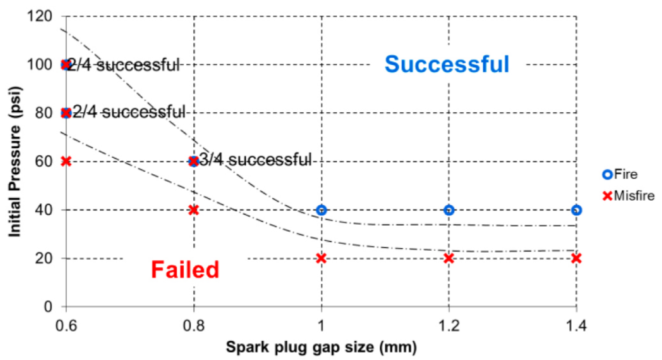


Figure 8. Effect of spark plug gap size and initial mixture pressure on ignition under quiescent condition (10% EGR methane-air mixture with Φ=0.6, 423 K, 2 A primary current).

Understanding the trend of factors affecting spark ignition will be important later in selection of test conditions as they are necessary to make the ignition behavior sensitive to the target variable, which is discharge pattern in this work.

Hypothesis on Multiple Discharges Ignition

Preliminary tests were also undertaken to observe flame kernel behavior under flow motion. The turbulent flow generated by the shrouded fan was able to wrinkle the ignited kernel as well as detach it from the spark plug down the stream. Extinction of kernel occurs when discharge energy is not sufficient.

A hypothesis is proposed based on observations. A condition was set to quenching of kernel when using a single discharge while multiple discharges are designed for the successful ignition. The target variable is the time delay/ duration between two consecutive discharges. Schematics in Figure 9 describe the mechanism of kernel interactions.

Figure 9 (a) describes the extinction of a flame kernel generated by a single discharge. The flame kernel is blown away from the electrodes and combustion energy dissipates quickly in the flow field. If the second discharge happens immediately after the first one, as shown in Figure 9 (b), the second spark will spark into the hot product of the first kernel without generating the second flame kernel, which will quench similarly as the single discharge case. When the second discharge is added with moderate delay relative to the first, it could be seen in Figure 9 (c) that the second flame kernel is initiated by the second discharge. Driven by the flow motion, the two kernels are able to achieve some overlapped regions in space and a survival kernel initializes from the overlapped region. If the second discharge is placed with a further delay as seen in Figure 9 (d), the two kernels are not able to overlap due to the flow motion, thus resulting in two individual extinctions of single kernel similar to the case in Figure 9 (a). It is suggested that the successful kernels interaction can be achieved by properly controlling the secondary discharge timing with respect to the first discharge timing.

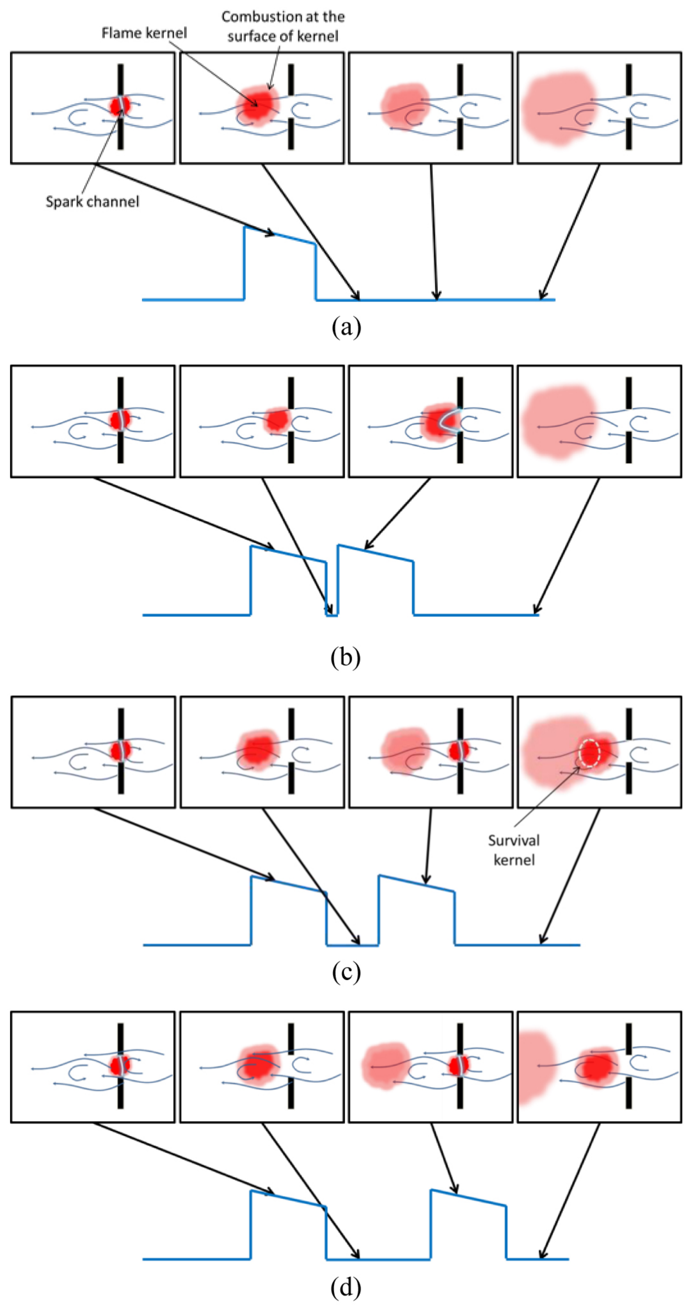


Figure 9. Hypothesis of flame kernels interaction with multiple discharge: (a) single discharge (failed ignition), (b) 2-strike discharge with too short delay (failed ignition), (c) 2-strike discharge with moderate delay (successful), (d) 2-strike discharge with too much delay (failed ignition).

Selection of Experimental Conditions

Due to the limitation that the constant volume combustion vessel is not capable of duplicating exactly the same engine conditions of mixture temperature, flow field, and transient performance, it will be necessary to wisely determine the test conditions carried on in the CV to acquire the most representative conceptual results.

Here, experimental conditions are selected to investigate the effectiveness of flame kernels interaction with flow. The CV temperature is fixed at 423 K which is beneficial to ensure the sealing of the vessel. Lean and dilute methane/air mixture (10% EGR, Φ=0.6), mixture pressure (4.1 bar), small gap size (1.2 mm) and high flow motion (8000 rpm fan speed) are adopted mainly to make the mixture relatively difficult to ignite, so that a more significant level of discharge current could be applied and tested. The duration of each strike is limited to 100 µs and preliminary experiments showed that a single discharge with 8 A peak primary current resulted in quenching of a single kernel. Test conditions are determined with this single discharge pattern taken as a starting point and expanded to 2-strike discharges of different delays, as listed in Table 1.

Table 1. Summary of experimental conditions.

Mixture	10% EGR mixture with Φ=0.6 (5.5% CH_4, 18.5% O_2, 75.4% N_2 and 0.6% CO_2)
Initial temperature	423 K
Initial pressure	4.1 bar
Spark plug	1.2 mm gap size double fine wire
Flow generation	8000 rpm fan speed
Shroud	Φ0.35” hole on side surface
High speed camera	30,000 fps frame rate
Primary current	8 A for each discharge
Discharge pattern	• Single discharge • 2-strike discharge with variable delay time

Test Procedure

Lean methane (CH_4) - air mixture at the equivalence ratio of 0.6 with carbon dioxide (CO_2) as a diluent was used to mimic EGR (exhaust gas recirculation) conditions in engine cases. In preparation of the combustible mixture, the initial compositions of the mixture, CH_4, CO_2, O_2, and N_2 were premixed in a 10-L mixing vessel and the partial pressures of each gaseous component are set up to match the target equivalence ratio and EGR level. During the test, the CV is heated up to 423K, and the premixed mixture with CO_2 as diluent is filled into the CV through the inlet valve till a desired initial pressure is reached. All valves are closed to ensure the CV sealed well before triggering the spark. Data acquisitions including the high speed camera are synchronized with the spark event. N_2 is introduced to purge the CV after each test run.

RESULTS AND DISCUSSION

Experiment has been conducted to confirm the proposed mechanisms. Nine discharge patterns have been tested and explicitly presented to show corresponding flame kernel behavior. Detailed discussions will be focus on quenching phenomenon, interaction of flame kernels and a quantitative analysis on required timing for 2-strike discharge.

Unexpected cases occur during the tests because of the fact that the flow field generated by the shrouded fan has limited range in space as shown in Figure 10, so that the flame kernels have chances to move out of the effective flow field and develop to a laminar-like flame front. These unexpected cases may provide misleading information to ignition statistics. It is necessary to define the effectiveness of the test runs. In this paper, only “effective” cases were selected based on observation that the flame kernels stayed within the flow field range.

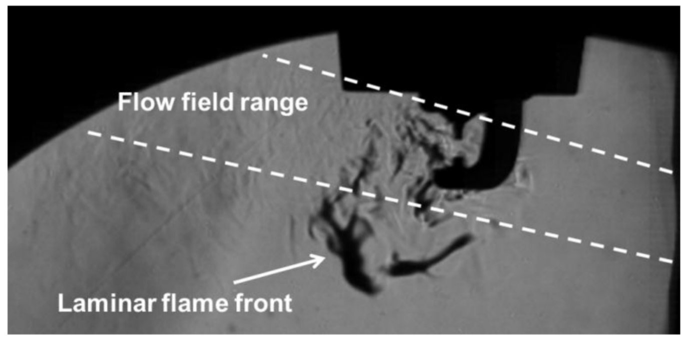


Figure 10. Sample image of unexpected case: flame kernel moves out of the effective flow field range.

Flame Kernel Quenching in Turbulent Flow

Figure 11 shows the double fine wire spark plug with a 1.2 mm gap size that is used for the current work. Both the center and ground electrodes have a piece of thin wire attached.

Figure 11. Double fine wire spark plug with 1.2 mm gap.

Discharge energy can be estimated with equation 1. The first term in the right hand side accounts for breakdown and arc mode energy released within 1 µs after breakdown, where C_{total} is an estimation of secondary circuit impedance. The second term integrates the energy released during the rest of

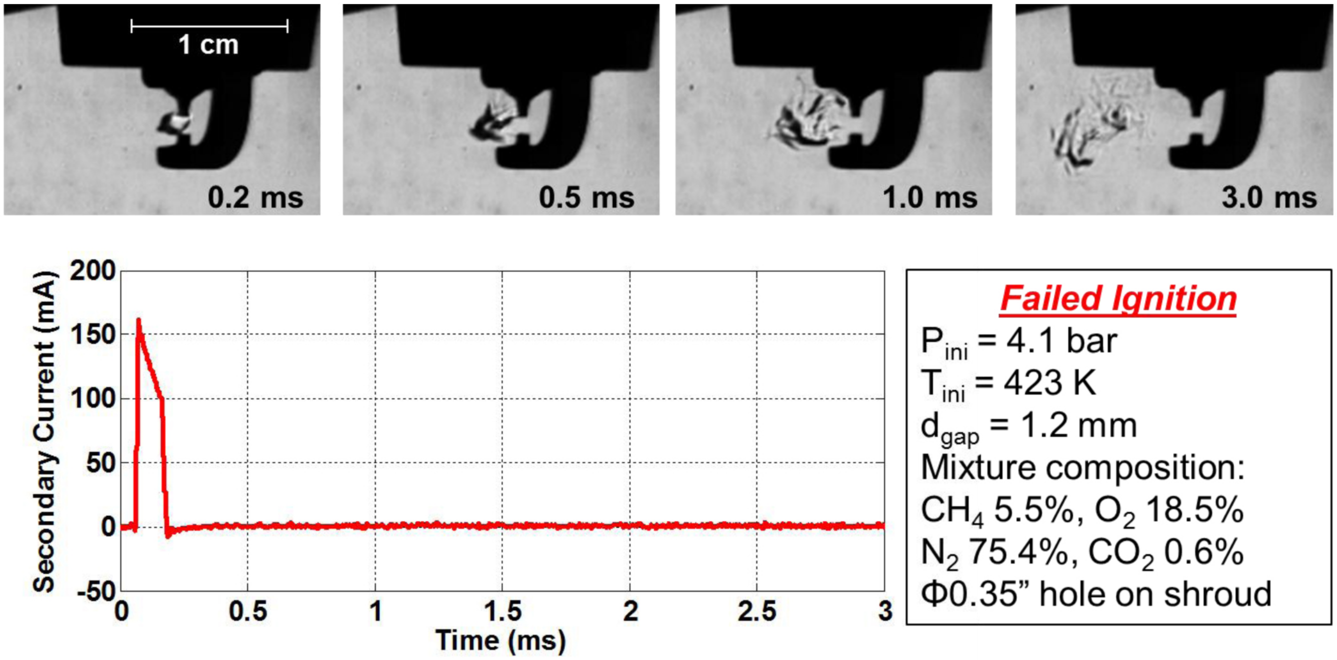


Figure 12. Flame kernel development with a single strike discharge (failed ignition).

the discharge period and can be treated as glow discharge energy.

$$E = \frac{1}{2} C_{total} V_{peak}^2 + \int_{\substack{discharge \\ duration}} i(t)v(t)dt \tag{1}$$

Total energy released from a single discharge in the current study is approximately 6 mJ.

Figure 12 shows four snapshots from the high speed images as synchronized with the discharge current waveform (truncated waveform and 100 µs discharge time). The shrouded fan produces cross flow from right to left in the figures and the outline of spark plug electrodes can be seen in the schlieren images.

It can be seen that a flame kernel is generated immediately after this single discharge. This kernel features a wrinkled surface where reaction occurs and contains hot products while the surrounding unburned gases are intact at initially low temperature. Under the tested flow condition, this flame kernel was able to keep an ellipsoid-like shape up to 0.5 ms after the triggering of discharge, which can be recognized from the second snapshot plate. Later, flow plays an important role in disassembling the bulk of the flame kernel into several smaller sized flame kernels. As can be seen in the snapshot of 1.0 ms, the previously large dark area on the image separates into several smaller disconnected dark areas. The localized disconnected flame quenches easily because of insufficient energy content and results in failed ignition, where most of the combustible mixture is kept unburned.

Interaction of Two Flame Kernels

Efforts have been undertaken to achieve successful combustion in turbulent lean and dilute mixture. The second discharge of the same amplitude and duration (8A and 100 µs, respectively) is added, which doubles discharge energy.

Figure 13 shows snapshots for flame kernel behavior with 2-strike discharge and a 0.7 ms delay set between the two strikes. The formation of a flame kernel can be recognized on the 0.5 ms image. The right-hand-side surface of the flame kernel becomes concaved into the volume due to flow effect. The bright channel shown in 0.7 ms image indicates the appearance of the second electrical strike. It can be seen that this electrical discharge channel exists in the volume of the existing kernel. The 1.0 ms image shows that the second discharge failed to generate the second flame kernel as most of the electrical energy was transferred to the combustion product of the first kernel. In fact, this extra discharge energy provided by the second strike slowed down the heat dissipation process of the first flame kernel, as there are still hot areas 5.0 ms after the first strike while the hot area is rather small in the 3.0 ms image of Figure 12 (single discharge case). However, the overall effective ignition of the mixture is still failed due to the ineffectiveness of the second strike in this case. Situation changes when the delay time is set to 1.0 ms. Figure 14 shows snapshots of flame kernel behavior with 2-strike discharge and a 1.0 ms delay. Unlike the 0.7 ms delay case, the second spark channel exists outside of the first kernel (1.0 ms image), which generates the second flame kernel as shown in the 1.2 ms image. The two flame kernels are close enough to each other in space to reduce heat loss through overlapping area, so that a relatively large

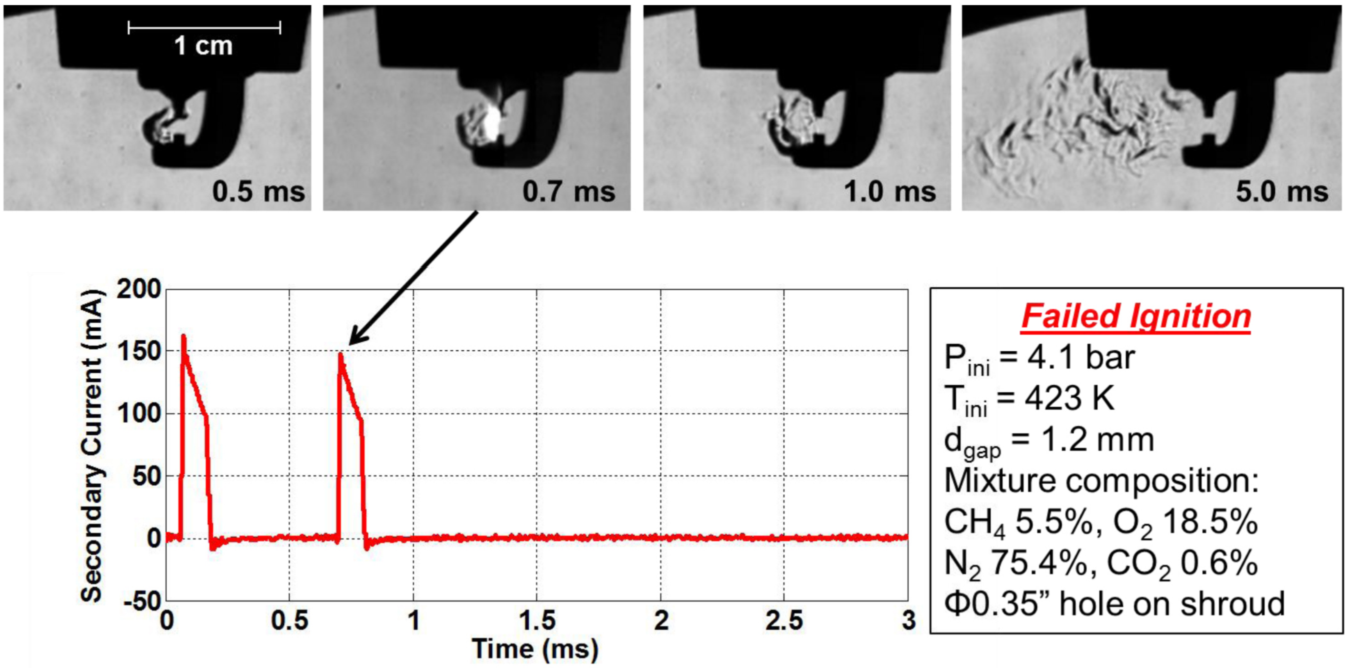


Figure 13. Flame kernel development with 2-strike discharge with 0.7 ms delay (failed ignition).

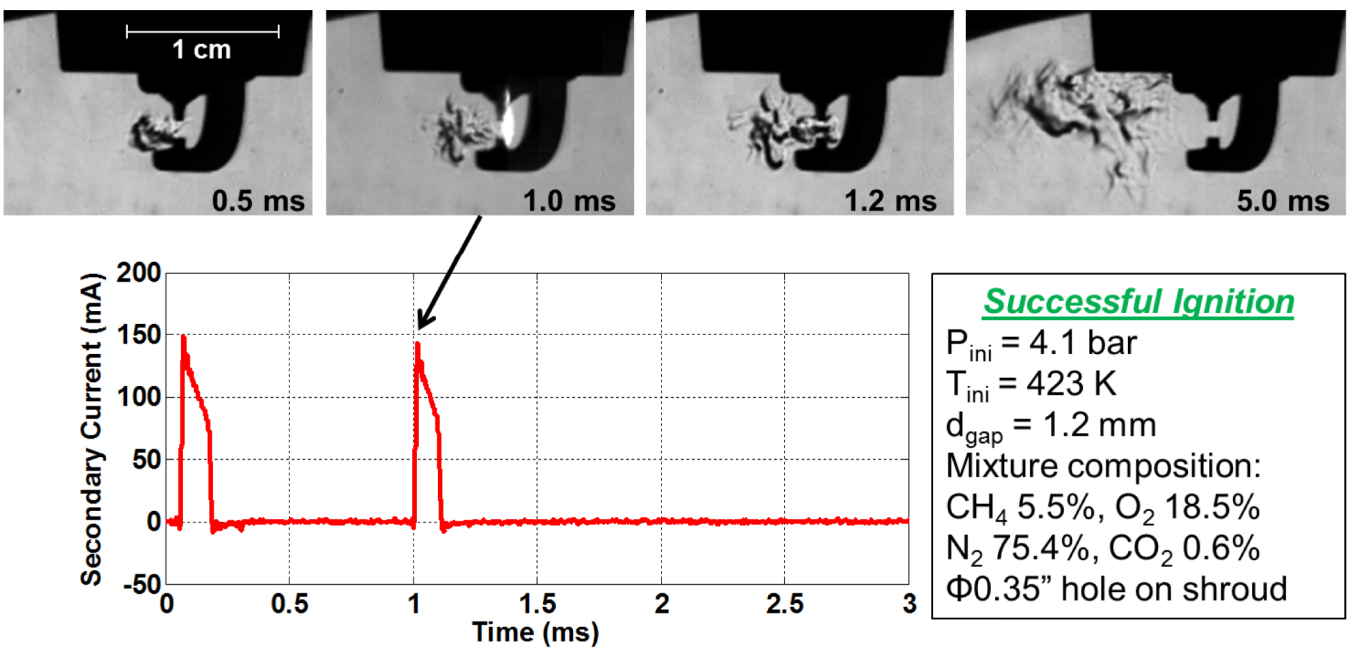


Figure 14. Flame kernel development with 2-strike discharge with 1.0 ms delay (successful ignition).

volume of surviving flame kernel is generated (5.0 ms image) and leads to a propagating flame later.

While this 2-strike discharge strategy appears to be effective with 1.0 ms delay between discharges, further delay of the second discharge results in the failed ignition again. Figure 15 shows the waveform of secondary current for a 2-strike discharge with 1.6 ms delay. As can be seen in the 1.8 ms snapshot of Figure 15, there are also two flame kernels generated by the two spark discharges, but the failure for the two kernels to overlap and merge with each other results in two individual quenching events.

A series of tests of 2-strike discharge cases with different delay times (from 0.4 ms to 2.5 ms with a step of 0.3 ms) have been conducted. With each individual discharge of 100 μs, all these cases have similar energy levels. Figure 16 shows the effectiveness of 2-strike discharge in ignition as a

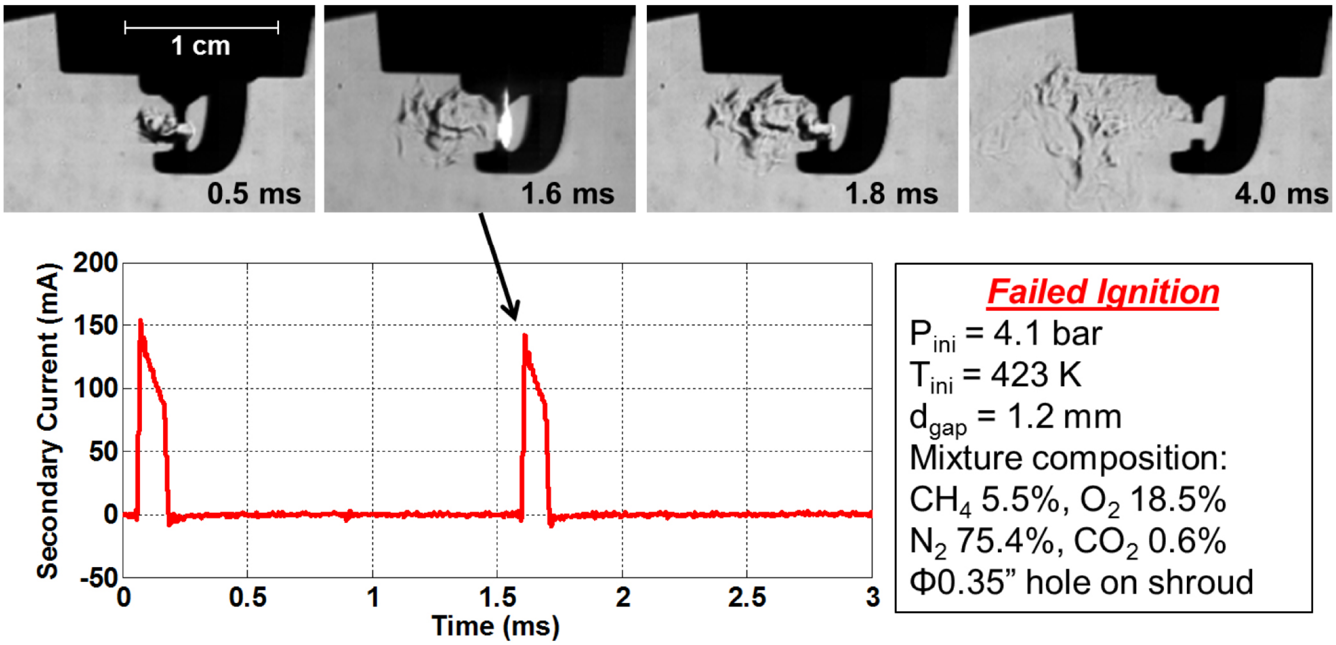


Figure 15. Flame kernel development with 2-strike discharge with 1.6 ms delay (failed ignition).

function of the delay time. It can be seen that the 2-strike discharge is only valid for a very limited window of delay times as represented by the green-color region in Figure 16. Successful ignition requires two flame kernels closely located in space to reduce significant heat loss. Under the tested conditions, when the delay time is less than 0.7 ms, ignition failure happens because the second strike discharges into combustion product and no second flame kernel is actually generated for interaction; when the delay time is longer than 1.6 ms, ignition fails due to the two flame kernels cannot overlap and interact. Due to the instability of the turbulent flow field, some "gray zones" are expected at the boundaries between each region, in which test results could show an intermittent manner.

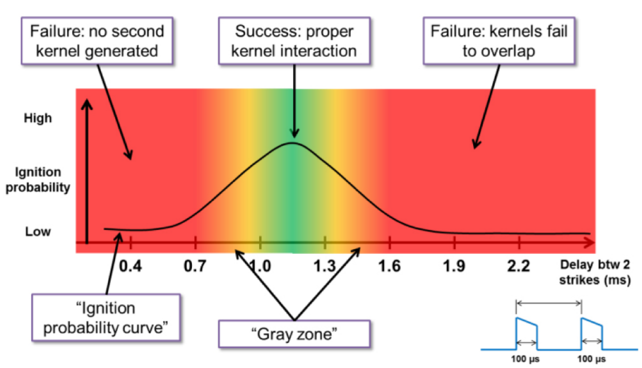


Figure 16. Effectiveness of 2-strike discharge as a function of delay time between two strikes.

Quantify Timing Requirements for 2-Strike Discharge

It can be concluded from the above observations that the timing setup for 2-strike discharge could be critical in its ignition phenomenon and is closely related to the local flow field in the vicinity of the spark plug gap. An attempt is made to quantify this requirement to achieve successful ignition for 2-strike discharge.

A schematic in Figure 17 is provided to show the interactions of flame kernels. Assumptions are that the flow velocity is constant during the ignition event and the center of each flame kernel moves with the same translational speed as the flow field from right to left in the figure. The radius of the flame kernel also increase while the kernel is translating, and $r(t)$ is used to denote the radius of the first flame kernel. The delay time between the strikes is denoted as Δt and u is the mean flow speed.

Based on the observation from test results, flame kernel becomes detached from the spark plug gap once the discharge ends. As shown in Figure 17 (b), when $t = \Delta t$, the center of the first flame kernel moves to a distance of $u \times (\Delta t - t_{d1})$ from the spark plug gap. To ensure the second spark discharge into fresh mixture for the second flame kernel, it is necessary that

$$u \times (\Delta t - t_{d1}) > r(\Delta t) \tag{2}$$

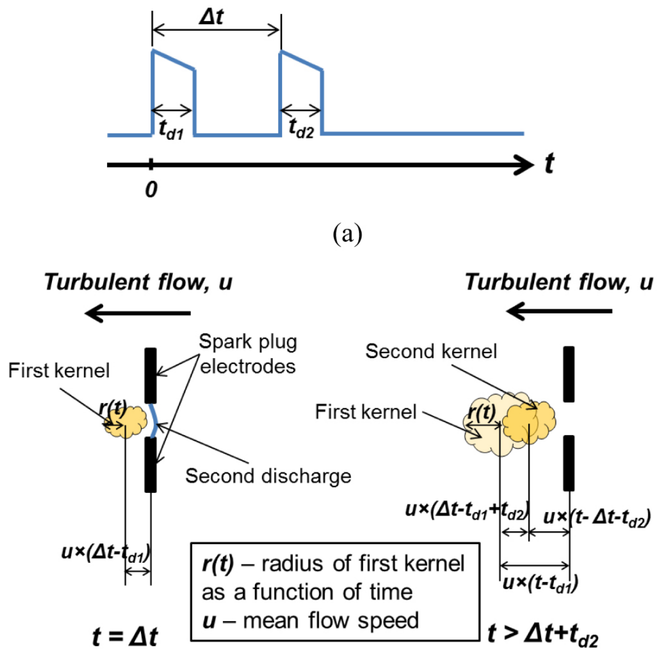
When $t > \Delta t + t_{d2}$, it is necessary to keep the distance between the centers of the two kernels less than a threshold value l_{th}, as indicated in Equation 3. A certain instant time needs to be specified to evaluate the threshold distance l_{th}, which should be a function of kernel radii and time.

$$u \times (\Delta t - t_{d1} + t_{d2}) \le l_{th}(t, r_1(t), r_2(t)) \tag{3}$$

As a summary, the range of delay time for successful ignition can be defined as in Equation 4.

$$\frac{r(\Delta t)}{u} + t_{d1} < \Delta t \le \frac{l_{th}}{u} + t_{d1} - t_{d2} \tag{4}$$

In addition, it would be necessary to provide sufficient discharge energy on the primary coils to ensure breakdown for each discharge.



(a)

(b)

Figure 17. Schematic of proposed ignition mechanism: (a) timing diagram and (b) schematic of kernel locations.

The flow field generated by the shrouded fan is relatively difficult to evaluate for the present setup. In order to determine the threshold distance l_{th}, further research is necessary to understand its correlation with corresponding kernel radius size at the certain instant time.

However, it should be pointed out that the delay time range described in Equation 4 is only one sufficiency but not necessity for producing successful ignition. Other type of discharge patterns, such as single discharge with long duration, could also be effective under some engine conditions [5, 14]. Equation 4 only describes the timing requirements to generate ignition with proper interaction of two flame kernels.

CONCLUSIONS

As part of a larger program to understand the ignition system requirements and performance under dilute conditions in modern direct-injection engines, spark ignited flame kernel characteristics have been experimentally investigated in a constant-volume optically-accessible combustion vessel. A variable output ignition system (VOIS) has been developed which enables the independent control of ignition energy phasing and duration that has been applied in these combustion studies as well as in engine studies. Flow across the gap of the plug is controlled and modified by a shrouded fan to simulate the in-cylinder flow motion in the engine.

With lean and dilute mixtures with turbulent flow across the face of the j-gap of the plug, flame kernel formation and successful and unsuccessful (extinction) ignition is observed dependent upon the phasing of two discontinuous discharges. A conceptual model and interaction mechanism of flame kernels from multiple discharges has been proposed and characterized for successful ignition. As a summary, the following conclusions are drawn:

• The observations with two short discontinuous discharges show that a critical phasing exists when two independent flame kernels are formed and joined to provide successful ignition of the bulk gas. Phasing shorter than this does not provide sufficient flame kernel volume and extinction occurs. Longer phasings result in independent flame kernels which independently dissipate without successful ignition of the charge. In the intermediate phasing, either one single kernel is formed as the flow has not had time to convect the kernel from the gap or two separate kernels form and join and the resulting synergy and expanded flame kernel volume results in successful ignition.

• Unlike laminar flow which expands the surface of flame kernel, turbulent flow has an effect of wrinkling the kernel surface as well as collapsing the kernel into several separate smaller sized flames, which are rather vulnerable to local extinction due to low energy content;

• The conceptual model proposes that a survivable flame kernel will result if the total time of the application of energy is greater than a minimum value and the gap between discharges is smaller than a value (l_{th}) such that there is synergy between flame kernels in the discontinuous discharge case.

• This energy and phasing with parameters in the conceptual model are dependent upon many factors, but it is clear that there is a strong coupling between flow and discharge duration.

• Testing and observations in the combustion vessel with other flows and discharge patterns have validated this conceptual model with the results presented here representative of the trends observed with different dilution, flow velocities, energy levels, and phasing.

• Testing in engine studies as part of this program with the VIOS also validated the proposed conceptual model [14]. That is at a fixed energy level the duration of the discharge is a critical parameter and there is an optimum phasing in dual discharge systems that provide a synergy for improved combustion stability and misfire elimination with dilute combustion. In these studies a wide range of phasing from overlapping to continuous to discontinuous discharge has been studied.

FUTURE WORK

It is the long-term goal of this work to further quantify through the coupled studies of combustion vessel and engine studies the requirements for ignition systems in modern direct injection engines under dilute homogenous conditions with high in-cylinder flow. An effort will also be spared to understand the flow field strength effect on this conceptual model. The results presented here provide an important insight into the important interactions. These interactions continue to be studied to further the conceptual model of the process, to provide quantitative data for requirements and to develop and validate ignition models for CFD and engine simulation codes.

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DEFINITIONS/ABBREVIATIONS

u - Mean flow speed

r(t) - Radius of flame kernel as a function of time

Δt - Delay time between two strikes

l_{th} - Threshold value for distance between flame kernel centers

SI - Spark ignition

CI - Compression ignition

PFI - Port fuel injection

UHC - Unburned hydrocarbon

EGR - Exhaust gas recirculation

COV - Coefficient of variation

IMEP - Indicated mean effective pressure

PLIF - Plainer laser induced fluorescence

CV - Combustion vessel

VOIS - Variable output ignition system

ICCD - Intensified charge-coupled device

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