

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 NO_x 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 CO₂ 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.

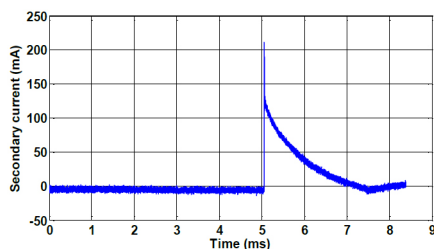


Figure 1. Natural decay type of discharge pattern from a conventional inductive coil ignition system.

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].

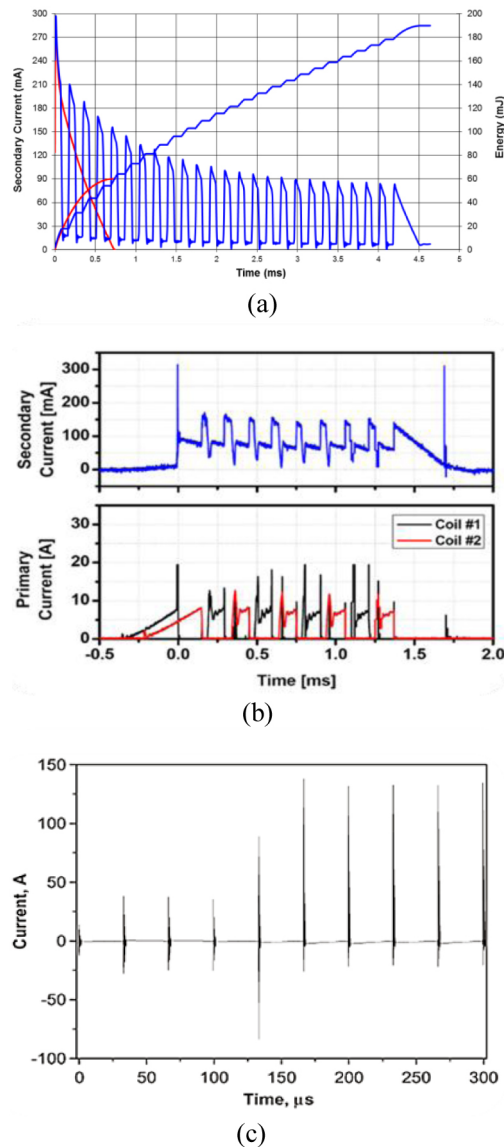


Figure 2. Secondary current waveforms of three discharge patterns: (a) multi-spark discharge, (b) continuous discharge, and (c) repetitive pulse discharge.

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 CO₂ 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.

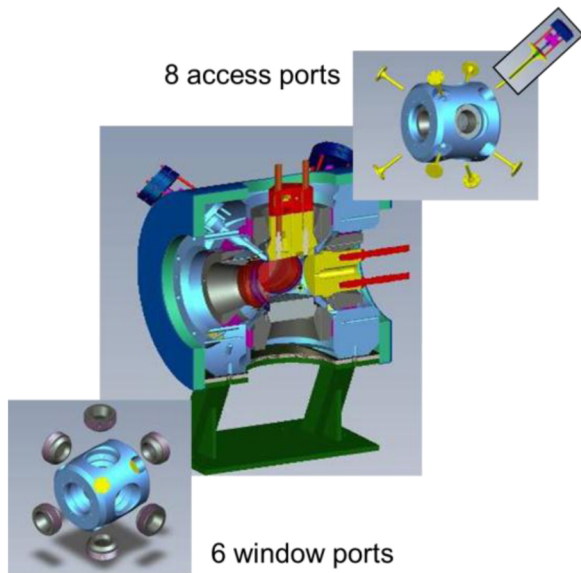


Figure 3. Constant volume combustion vessel (CV).

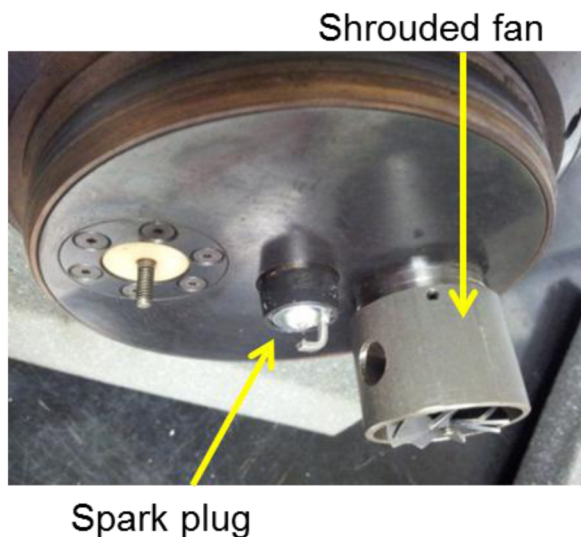


Figure 4. Top port window setup for CV, left fan has been removed. Left fan shaft is necessary to seal the CV

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 ($f_l = 750$ 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 $2 \text{ mm} \times 5 \text{ mm}$ 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 ($f_l = 100$ 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.

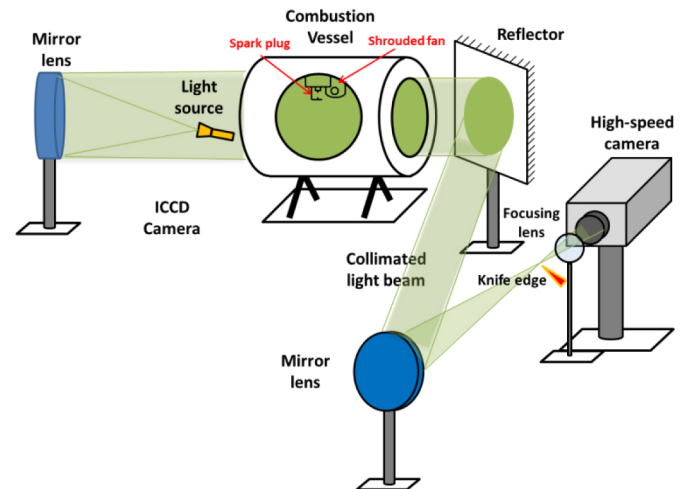


Figure 5. Optical setup for schlieren imaging.

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