Review on performance of High energy ignition techniques

Jubin V Jose, Sreenath V R*

1,2 Department of Mechanical Engineering, Government Engineering College, Thrissur
jubinvjose@gmail.com
*vrssreenath2007@gmail.com

Abstract

Ignition systems are the fundamental parts of spark ignition engines which determine the engine efficiency and pollutant emission. With the recent developments in engine technology significantly high spark energies are required. This paper reviews progress in alternative ignition systems that supply high energy sparks and more efficiently transfer energy to the gas mixture. The improvement in performance parameter of a spark plug such as net heat transfer rate, flame development time, exhaust gas emission rate are compared with conventional ignition systems. This paper also tries to identify critical research gap and also the advantages and limitations of advanced systems with reference to the advanced researches reported in this area.

Keywords: Combustion, Engine, Exhaust Emission, Flame propagation, High Energy Ignition

1. Introduction

Spark ignition engines evolved in 19th century has revolutionised human life in terms of transportation via automobiles. The developments of electronic controls to trigger the systems and the use of distributor less systems have produced spark ignition systems with outstanding effectiveness and reliability. However, some future developments in SI engines may require significantly higher spark energies. Higher spark energy and power can be beneficial to early flame growth and improve tolerance to the higher rates of EGR used to reduce $NO_x$ emissions

2. Principle of Ignition

W Maly and his co-workers [1] in 1978 published a paper in new aspects of ignition where they identified four phases in ignition.

They are

a) Pre-breakdown
b) Breakdown
c) Arc
d) Glow

In pre-breakdown phase voltage is applied to air gap offering infinite impedance. With sufficient high voltage above threshold to cause break down of free electrons which accelerate towards the anode. If the voltage drop is high enough, electrons gain energy from it to ionize the molecules lowering the impedance of the air gap. As the steady supply of electrons is necessary to make gap conducting additional energy transfer processes such as radiation from excited ions are required. The increasing concentration of electrons and ions reduces the impedance of air gap and thus current flow begins and breakdown is achieved. Once breakdown is achieved current flow rapidly increases which simultaneously increases the energy and power delivered to the spark channel. The added energy further ionizes the gap thus reducing the voltage required to maintain the arc.
3. Breakdown Ignition System

In breakdown phase current flow rapidly increases which simultaneously increases the energy and power delivered to the spark channel. The added energy further ionizes the gap thus reducing the voltage required to maintain the arc. Thus the breakdown phase lasts only for a few nanoseconds and is characterised by efficient transfer of electrical energy to the spark plasma. Since the process is so rapid the energy stored in the electrode near the gap is deposited into the volume between two electrodes and this energy fully dissociated the gas in the volume.

Ziegler and his associates [1] designed a ignition circuit that would deliver maximum efficiency of energy at breakdown phase. Thus designing a circuit that would deliver most of energy at break down phase increased the engine efficiency and enhanced early flame growth. The discharge time was 10000 times shorter than conventional ignition and it was more powerful since it delivered great energy in short period of time. Power was estimated to be in the range of 1-2 MW while conventional system was in the range of 10W-1KW. Rapid spark delivery improved the efficiency of engine since heat loss was much smaller and thus it enhances early flame growth. Also an enhanced flame size was also witnessed. Break down ignition also reduced NO\textsubscript{x} emissions. The amount of NO\textsubscript{x} formed in an engine is dependent on the temperature history within the flame and the availability of oxygen to combine with the nitrogen. Fast burning engines can reduce the total time available for NO\textsubscript{x} formation but can also increase the peak temperature due to less time for heat losses.

4. Multiple Spark Plug Ignitions

In 1992 Yamamoto [3] experimented using multiple spark plugs arranged in such a way that the ignition starts simultaneously at both centre and perimeter of combustion chamber walls. The layout is as shown in figure

\begin{center}
\includegraphics[width=0.5\textwidth]{figure1.png}
\end{center}

**Figure 1** Multiple spark plug layout

The advantages include reduced flame travel distance which produces shorter burn durations, possible use of high compression ratio and improved fuel efficiency. Also reduced hydrocarbon emissions due to reduced quench area and reduced partial burns at high air fuel ratios. Also shorter ignition delay and reduced NO\textsubscript{x} emissions were also witnessed. The following graph shows the trend with respect to air fuel ratio.

5. Plasma Sustained Ignition System

In 1997 J.D. Dale [5] and his research associates investigated on performance of plasma sustained ignition system using plasma jet igniters. Plasma jet igniters use electrical discharges inside small volume cavities. The ionized spark is immediately moved away from the housing where it is created, to a location within the combustion chamber where the thermodynamic conditions are more favourable for rapid flame growth. Both use high energy electrical discharges inside small volume cavities.

\begin{center}
\includegraphics[width=0.5\textwidth]{figure2.png}
\end{center}

**Figure 2** Plasma jet igniter
Plasma jet igniters differ from a normal sparking plug in such a way that the discharge occurs in a small cavity which can be supplied with a suitable plasma medium by means of a small capillarity. The extremely high temperatures and pressures contained in the discharge cause the plasma to be ejected as a supersonic jet through an orifice. The igniter consists of a two tier spark energy delivery system. Initially a high voltage, low current discharge, similar to a conventional spark ignition discharge, is used to break down or ionize the gap. This is followed by a secondary low voltage, high current discharge which adds to the dominant part of the spark energy. The secondary energy is usually stored on a capacitor with a potential below that required to ionize the gap, usually about 1000 V, but once the gap has been ionized only about 100 V is required to maintain the discharge. The main spark discharge rapidly heats the gases in the cavity to a high temperature which simultaneously creates high pressure. The temperatures are high enough to produce a large number of ions and free electrons which are forced out of the cavity as a high speed jet. The results observed include

1) Extension in lean operation
2) Improvement in engine power
3) Improvement in engine efficiency

However when mixture was near stochiometric ratio very little improvements were found and basically there was no change in CO and HC levels in exhaust emission but \(NO_x\) levels were high due to faster combustion. The high energy electrical discharge in these devices tends to cause high erosion rates of the electrode metals.

### 6. Spark Ignition with No Ground Electrodes

In 2012 Ahmed A. Abdel-Rehim [6] investigated a group of four spark plugs with different number of ground electrodes to explore their impact on the engine performance and energy transfer from flame to the spark.

A group of four spark plugs were used in the study. The four spark plugs have similar point central electrodes but with different number of ground electrodes. The test plan involved operating the engine with spark plug with only single ground electrode and modified spark plugs with no, two and four ground electrodes. The layout of spark plugs is shown below

![Figure 3 Layout of spark plugs](image)

A series of tests were conducted on a single cylinder, spark ignition engine. The engine was connected to an ac motor dynamometer used to load and control the engine speed with a rated power of 12 kW. A single experiment consisted of 180 cycles. Each cycle has 720 points generated with a resolution of 1 crank angle degree and following parameters were evaluated.

The following result was obtained by evaluating all the parameters mentioned above and performance of spark plug with no ground electrode is as follows

a) The plug, type-D, that performed the best, was a plug with no ground electrode where the amount of heat loses was the lowest and there was no obstacles affecting the flame growth.

b) A reduction of 7.3% in the time required to burn 10% mass of the mixture was recorded for this spark plug compared to SP type-A

c) An increase of 4.4% in IMEP was observed.
These results were witnessed due to the fact that the spark plug with no ground electrodes has

a) no obstruction in front of the centre electrode preventing the flame from growing in any direction
b) no much mass of metal affecting the heat and the temperature of the flame
c) Higher ignition energy aids combustion and extends flammability limits which helps in the main combustion period

7. Laser Ignition

In 2013 Mohamed H. Morsy(8) investigated possibility of use of laser ignition technique and evaluated its performance with respect to spark ignition. Laser-induced spark is a reasonable point energy source in which the amount of energy, the rate of its deposition and ignition timing can be controlled precisely. It also permits the choice of optimal ignition location, which is not easy in conventional ignition systems. In addition, the absence of a material surface in the vicinity of the ignition location minimizes the effect of heat loss during flame kernel development and hence, the lifetime of a laser ignition system is expected to be significantly longer than that of conventional spark ignition systems. Furthermore, for equivalent amounts of system input energy delivered to the spark by the laser ignition system provides a much larger initiating spark volume as compared to an electrical spark. Moreover, laser ignition is capable of providing multipoint ignition sites that can be controlled to ignite gaseous combustible mixture either sequentially or simultaneously rather comfortably as compared to conventional electric ignition systems using spark plugs.

In laser ignition there are four different mechanisms by which laser light interact with a combustible mixture to initiate an ignition event.

a) Thermal initiation- A low energy long wavelength laser radiation is incident on a target material that is a strong absorber, which can be solid or gaseous, combustible mixture and a thermal initiation takes place by utilizing infrared (IR) laser energy to vibrationally excite a specific highly absorbing species within the combustible mixture to induce ignition. Ignition takes place when the absorber transfers sufficient energy to the combustible mixture to cause auto ignition.

b) Photochemical ignition: Photochemical ignition occurs when a high energy photon dissociates a molecule allowing the ionized constituents to react with the surrounding gases. The primary difference with conventional ignition is that the photon energy is the incident radiation and the absorber is the gas to be ionized and not a solid or gas. Thermal initiation utilizes IR laser energy to vibrationally excite non-combustible yet highly absorbing species within the combustible material to induce combustion. The photochemical process employs ionizing radiation in the ultraviolet (UV) wavelength range or higher to initiate ignition.

c) Resonant breakdown: Resonant laser ignition is initiated by the dissociation of target molecules or atoms by the non-resonant multi-photon ionization process. The dissociated atoms or molecules are then resonantly ionized via multi-photon ionization by continued laser illumination.

d) Non resonant breakdown: Non-resonant breakdown occurs when a laser pulse of sufficient power is focused to a sufficiently small spot and the electrical field component of the focused light is strong enough to influence the gas molecules and initiate the electrical breakdown of the gas. Once the breakdown potential is exceeded, a plasma discharge ensues which can produce localized temperatures.

8. Microwave Assisted Spark Ignition

In 2013 Benjamin Wolk[7] and his co-researchers developed a flame ignition technique combining the energy of microwave to conventional spark ignition. Plasma-assisted combustion research, which investigates combustion enhancement through electromagnetic interactions in gases, has the potential to improve combustion systems. Generation or enhancement of plasma in a combustion environment through the use of microwaves is discussed in this paper. Plasmas are commonly categorized as either thermal or non-thermal. In thermal plasmas, the electron energy is in equilibrium with the energy of the bulk gas, thus characterizing thermal plasmas with high gas temperatures and high levels of ionization. In non-thermal plasmas, energy transferred to electrons enhances reaction without causing large increases in gas temperatures. The presence of reactive excited species and radicals can increase the overall rate of reaction in non-thermal plasma, while requiring lower energy input than thermal plasma. In non-thermal plasma energy transfer from electromagnetic waves to free electrons in gases results in inelastic electron collisions with ions and neutrals having sufficient energy for initiating electronic and vibrational activation, molecular dissociation and ionization reactions. Electron impact can cause dissociation of gas molecules into more-reactive radicals that accelerate combustion reaction rates. Electron impacts enhance ionization reactions that expand the number of free electrons in the plasma, increasing the possibility of chemistry enhancement by energetic electrons. One method of delivering energy to electrons in gases that has seen considerable research attention is through microwaves. Microwaves have primarily been used in combustion research to promote stability by increasing flammability and flame speeds through kinetic effects.
In the experiment the microwave assisted spark plug initiates plasma using a capacitive discharge spark which enhances electron energy and expands the plasma by emitting microwaves into the spark zone. Microwaves generated by a magnetron at a frequency of 2.45 GHz are transmitted through the spark plug insulator into the combustion chamber. In the combustion chamber, the microwaves are absorbed by the free electrons in the spark discharge, generating non-thermal plasma. The same combustion was initiated with spark plug only mode and results were compared. The enhanced flame development using microwave for different stochiometric mixtures is shown below.

Also the enhanced ignition resulted in less flame development time compared to normal ignition. Greater enhancement was viewed in leaner mixtures and less enhancement near stochiometric mixtures, but net heat release remained the same. The enhanced ignition method resulted in extended ignition limit of 10 percent for lean mixture and 15 percent for rich mixture.

9. Corona Ignition

In 2013 DR. John burrows, Jim lykowski, Kristopher mixell [9] developed an advanced corona ignition system. As the name suggests the corona which is high energy density pack of electrons is utilized for enhancing ignition. The ignition system has two components. The first is the two-piece igniter assembly which is mounted in the cylinder head very much like the traditional spark plug and ignition coil. The igniter assembly contains the inductor at the top and the firing tip at the bottom. The second system component is a controller which computes the trigger signal from the engine control unit and converts the 12 V DC electrical supply into the required AC voltage at a resonant frequency, which is fed forward the igniter. At this frequency the igniter emits a strong electrical field with up to 72kV at the tips of the firing end. Originating at the four electrodes of the igniter tip, the field extends into a large volume of the combustion chamber. The energy content of the electrical field excites the air fuel mix near the electrodes until it turns into a plasma with a high content of charged particles (ions), a process that only takes several nanoseconds as opposed to up to 70 μs.
in the case of spark ignition arc breakdown. When the electron density reaches a sufficient level, multiple long streams of ionised gas extend into the combustion chamber and ignite the charge. The name corona ignition refers to these visible streams of ionised gas. The air-fuel mix is ignited in several areas at the same time, which speeds up the burn rate and results in a fast, harmonious combustion. In contrast to the spark plug which produces a single short arc, the four ion streams originate from the tip of an electrode and extend outward into the combustion chamber. Due to the low current and low heat discharge, there is no electrical erosion. Therefore the corona spark plug is not subject to the same level of wear as a conventional plug. The biggest benefit is the vast volume which is reached by the corona. In the case of a spark plug, the electric arc is always limited to the small gap between the two electrodes. The only way to increase the energy of this ignition source is to use a higher current and to prolong the arc duration. Both measures increase the energy consumption of the ignition system.

The benefits of corona ignition include:

a) Better conversion of fuel energy into mechanical energy due to rapid ignition and quick burning
b) Initial flame development and burn rate is faster
c) More thorough combustion
d) Extension of lean burn limits, when conventional spark plug permits air fuel ratio of 1.5, corona spark plug permits air fuel ratio of 2
e) Fuel efficiency improvement up to 30 percent
f) Fuel economy improvements up to 10 percent
g) High mean effective pressure
h) Lower $NO_x$ emissions

10. Radio Frequency Spark Ignition

In 2014 Antonio Mariani and Fabrice Foucher [10] performed a experimental activity in a spark ignition engine equipped alternatively with a conventional spark plug and a Radio Frequency Ignition System (RFSI). The application of an alternative radio frequency voltage keeps the electrons close to the spark plug electrode. A resonant RLC circuit is required, including an inductance inside the spark plug. The RFSI ignites a volume bigger than standard spark plugs due to the absence of the ground electrode, has a higher efficiency of the ignition energy delivery and ability to vary the spark duration depending on engine operating conditions.

In the RFSI an alternating, high voltage, electrostatic field generates excitation of high-energetic electronic states and ionization, increasing the number of free radicals. These radicals are responsible for chemical reactions in the air-fuel mixture which proceed exothermically, activating the combustion process. A relatively large amount of ionizing energy, up to an order of magnitude greater than conventional ignition systems that can be delivered to the combustion chamber. The RFSI is composed of a resonant transformer circuit which amplifies the input voltage delivered by an external supply unit. At the resonance frequency, the voltage amplitude reaches its maximum. Depending on the in-cylinder thermodynamic conditions, the breakdown voltage can be reached and the ignition is initiated. If the breakdown conditions are attained, the discharge is formed and the electrode voltage drops. The spark takes a multi-channel structure, allowing the ignition of a volume bigger than that of a standard spark plug.

Here the experiment was conducted:

a) Without intake air dilution
b) With intake air dilution of twenty percent of nitrogen

It is to be noted that high rate of combustion results in higher rate of pressure rise producing higher peak pressures at a point closer to top dead centre. This is desirable since peak pressure closer to top dead centre produce greater force acting through a large part of power stroke which increase power output of the engine. The flame advance required to cause maximum pressure increases with increase in equivalence ratio.

11. Conclusion

This review has focused on recent developments in ignition systems for engines. The systems presently in use are reliable, inexpensive to make and deliver adequate energy for automobile engines using gasoline fuel at near stoichiometric air-fuel ratios. However, if alternative fuels are to be developed further and if high compression, lean burn technology is used for future fuel efficiency improvements, then higher energy and possibly enhanced ignition systems will be necessary. There are several short term and long term possibilities. The short term could use multiple spark plugs with conventional coils or breakdown (short duration, high power) systems. For the long term, it is
suggested that more work be done on understanding the chemical kinetics of ignition processes which might lead to new concepts in ignition. The preceding discussion shows there are many possible replacements for conventional ignition systems. Each of the systems has certain inherent advantages. Most of the alternative spark systems have potential for high ignition energy when compared to the ignition systems which presently dominate the field. This higher energy is advantageous for engines running on very lean mixture avoiding the poor ignition reliability and irregularity which occurs in such mixtures. Let this additional energy ensure better ignition of present engines leading to greater engine efficiency, greater fuel economy and less exhaust emissions that dominate the roads. In summary, the current ignition system, with its low cost and high reliability, is well suited to providing the low ignition energy sparks but it is doubtful whether it will meet the rising engine capacities and the power requirements that is offered by the modern engines that ultimately lead to search for enhanced ignition system.

References

[9] DR. John burrows,Jim lykowski,Kristapher mixell (Corona ignition system for highly efficient gasoline engines-2013)