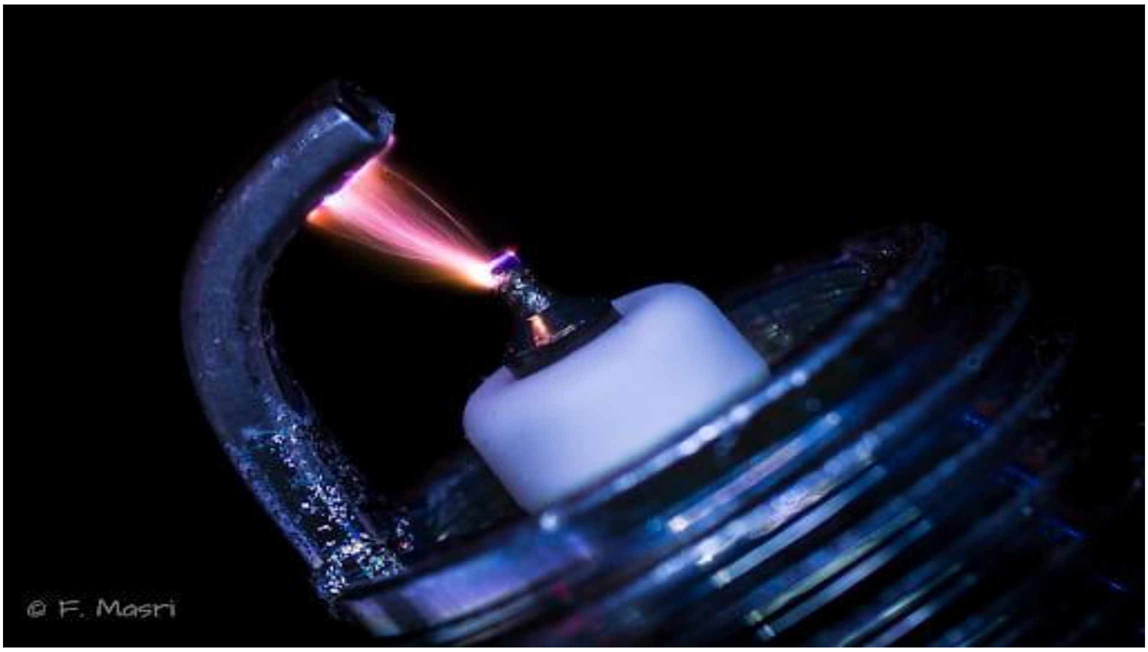
IGNITABILITY STUDY

OF

A SPARK-IGNITED HEAVY-DUTY ENGINE,

FUELED WITH NATURAL GAS (CNG)



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Project title:	*Ignitability Study of a Spark-Ignited Heavy-duty Engine, fueled with Natural Gas (CNG)*

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Anupam Saha, Lund, June 2021

Summary

In-order to meet today's stringent emission regulations of the European Union, the use of low-carbon fuels in ICE, for instance, Natural Gas (CNG)[1] is on the limelight. Due to the high knock-resisting properties of methane (high octane rating), the SI (Spark-Ignition) combustion process is the best match with CNG[1]. A major disadvantage with an SI engine is its low thermal efficiency mainly due to the engine, being throttled. Hence, in-order to increase its efficiency, diluted air (by means of EGR) can be a promising solution.

However, with the addition of EGR, combustion stability degrades, hence indicating a potential need for high Ignitability. A robust ignition system can be a solution to achieve high combustion stability by discharging high spark current and duration at the spark-plug gap, therefore, an excessive waste of spark energy in the combustion chamber. As an impact, it will lead to increase in wear in the spark plug electrodes, which is not desirable. Therefore, an experimental research is performed in a heavy-duty SI-ICE fueled with Natural Gas, in-order to study the ignitability requirements of the engine to attain robust combustion, even with high dilution/EGR level.

Three different ignition systems are considered in the experiment: a conventional Inductive Discharge Ignition (IDI) system, a Standard Capacitive Discharge Ignition (CDI) system, and an optimized CDI system using FlexiSpark™ Ignition Control Module (ICM), developed by SEM AB. The experiments are performed at different engine operating conditions to review the ignitability requirements with the change in engine load and RPM while adding dilution (by means of EGR). After comparing multiple spark discharge parameters of the ignition systems with respect to engine performances, it is found that the most influential parameter that governs the ignitability capability of an ignition system is *"Spark Power"*. By effectively varying spark power, the engine can still achieve stable combustion with minimal spark duration. Therefore, a significant amount of spark energy can be saved from being wasted by optimizing the spark discharge parameters, hence keeping the spark plug electrodes wear to a minimum.

Finally, a best suitable spark design strategy is proposed for the ignition systems tested at different engine operating conditions while assuring minimal waste of both spark power and energy in the combustion chamber and maintaining a stable engine operation with high EGR/dilution level.

Keywords: *alternative fuels, spark ignition, COV_{IMEP}, spark power, spark plug wear.*

[1] *Biogas is more preferrable to use in ICE for a sustainable environment since it is a renewable fuel.*

Table of Contents

Abbreviations

σ	Standard Deviation	
$\bar{x}$	Mean / Average	
$\frac{dQ}{d\theta}$	Heat Release Rate	[Joules/CAD]
γ	Specific Heat Ratio	
P	In-cylinder Pressure	[Bar]
$\frac{dp}{d\theta}$	Rate of change in Cylinder Pressure	[Bar/CAD]
V	Actual Cylinder Volume	[m^3]
$\frac{dV}{d\theta}$	Rate of change in Actual Cylinder Volume	[m^3/CAD]
n	number of measurements	
Icurrent	Spark Current	[mA]
I_{RMS}	RMS value of Spark Current	[mA]
Nm	Newton-metre	[$\frac{Kg.m2}{s2}$]

Acronyms

CAD	Crank Angle Degrees
ICE	Internal Combustion Engine
EGR	Exhaust Gas Recirculation
SI	Spark-Ignition
CNG	Compressed Natural Gas
TCO	Total Cost of Ownership
RPM	Revolutions per Minute
IMEP	Indicated Mean Effective Pressure
COV	Co-efficient of Variance
GHG	Green-house Gases
CO	Carbon monoxide
CO_2	Carbon dioxide
A/F Ratio	Air-to-Fuel Ratio
K	Kelvin
NVH	Noise, Vibrations and Harshness
C/H Ratio	Carbon-to-Hydrogen Ratio
IDI	Inductive Discharge Ignition

CDI	Capacitive Discharge Ignition
ICM	Ignition Control Module
SA	Spark Advance
MBT	Maximum Brake Torque
ATDC	After Top Dead Center
THC	Total Hydrocarbons
BSFC	Brake Specific Fuel Consumption
PPM	Parts per Million
MFB	Mass Fraction Burnt
CA_{50}	Crank Angle Degrees at 50% Mass Fraction Burnt
CA_{SA-10}	Crank Angle Degrees from Spark Advance to 10% Mass Fraction Burnt
CA_{10-50}	Crank Angle Degrees from 10% to 50% Mass Fraction Burnt
CA_{10-90}	Crank Angle Degrees from 10% to 90% Mass Fraction Burnt
AC	Alternating Current
DC	Direct Current
mA	Milliamperes
mJ	Millijoules
KV	Kilovolts
ms	Milliseconds
µS	Microseconds
RMS	Root Mean Square

List of Figures

List of Tables

1. Introduction

This chapter is intended to outline the background of the project, followed by problem definition, research objective and finally, the research questions associated with the project.

1.1 Project Background

The use of low-carbon fuels such as Natural Gas (CNG)[2] in heavy-duty engines is on the limelight as it is considered as one of the promising solutions to reduce CO_2 emissions, thereby meeting today's stringent emission regulations of the European Union. The SI combustion process has the best match with the properties of CNG (high octane rating), however, if the engine is throttled (by means of throttle valve), it will limit the efficiency. Therefore, diluted air (by means of EGR) can be a promising solution to push the efficiency by reducing both pumping and heat losses inside the combustion chamber. Furthermore, addition of EGR will also suppress the tendency of knocking at high engine loads.

The stability of combustion is a challenge for the enhancement of thermal efficiency of such engines, running on diluted air and fuel mixtures. A robust ignition system with high spark power and energy discharge at every operating condition can be a solution but at the potential cost of excessive spark plug electrodes wear. As an impact, this will finally lead to increase in the total cost of ownership (TCO) in terms of cost for labour, material, and downtime of a vehicle, which is not desirable.

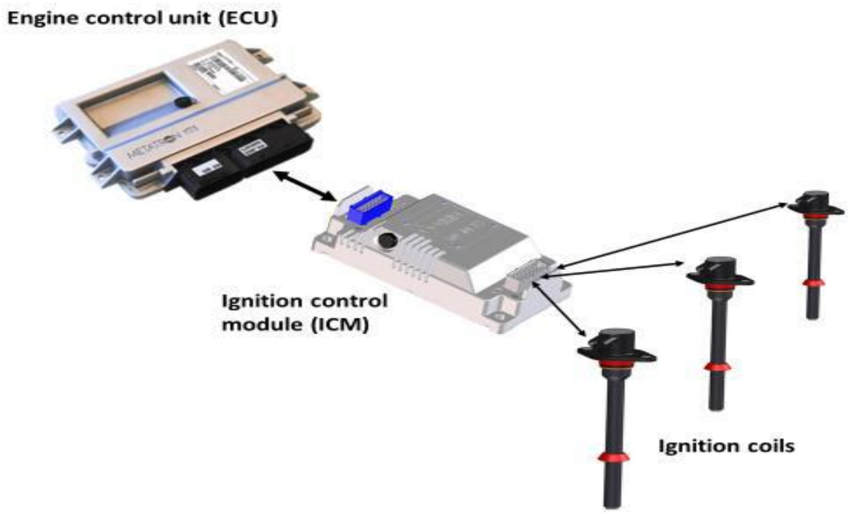


Figure 1: *A Typical Ignition System used in modern SI engines [17]*

Therefore, in-order to demand for optimum spark power and energy from the spark plug without being wasted in the combustion chamber while achieving high combustion stability, an appropriate spark strategy needs to be found for CNG fueled engines, which is the prime focus of this research.

The design strategy for the spark is obtained by determining the optimal values for the spark discharge parameters, for instance, spark current and spark duration at different engine loads and RPMs. Alongside, different types of ignition systems are used to make comparisons on the dispersion of spark power and energy inside the combustion chamber at various operating conditions.

[2] *Biogas is more preferrable to use in ICE for a sustainable environment since it is a renewable fuel.*

1.2 Problem Definition

Designing an optimal spark strategy for an engine by assuring negligible waste of both spark power and energy while achieving higher ignitability (stable combustion) at different operating conditions is challenging. High spark power and/or long duration will satisfy the ignitability requirements of the engine, but at the cost of excessive waste of spark energy in the combustion chamber, thereby also enabling more wear on the spark plug electrodes.

For instance, at low load condition of an engine, running on stoichiometric with EGR, low spark power with longer spark duration increases the probability to hit the favourable fuel-air mixtures[3], hence assuring robust combustion. On the other hand, at high loads, higher spark power is more desirable to initiate the breakdown of charged gas molecules between the spark plug electrodes because of the presence of high gas pressure inside the cylinder. However, spark duration can be significantly reduced because the temperature within the cylinder will be high enough to expedite the reaction, hence will reduce the early flame development time.

So, additional spark power with longer duration (after the combustion initiates) will lead to unnecessary waste of spark energy for any operating conditions.

1.3 Project Objective

Investigate and design a best suitable spark strategy for an SI Heavy-duty engine (running on CNG), while:

- Assuring negligible waste of both spark power and energy, thereby minimizing the wear on spark plug electrodes.

- Maintaining stable engine operation ($COV_{IMEP} \leq 2.5\%$), even with higher EGR/dilution level.

[3] *A favourable fuel-air mixture is formed when molecules of hydrocarbons are available (near the spark plug gap) in presence of sufficient oxygen molecules for combustion.*

1.4 Research Questions

The main research question for this project consists of the following:

How to design the spark in-order to minimize the waste of spark energy in an SI combustion engine (running on CNG), while maintaining stable engine operation at given operating points?

In-order to answer the main question, the following sub-questions must be answered:

- What are the most favourable engine performance measures to consider, in-order to design the spark, at a given operating condition?
- What are the appropriate spark parameters or combination of spark parameters to consider in-order to optimize and design the spark at individual operating condition?
- Which ignition system is the most favourable to use (capacitive or inductive) in-order to have minimal spark power and energy in the combustion chamber (at every operating point) while achieving low COV_{IMEP}?

The following chapter entails the review on the literature that were made in-order to clarify the aforesaid research questions and to comprehend the ignition systems, to be used in the experiments during the investigation.

2. Literature Review

This chapter provides an overview of the research that is based on the research questions, as mentioned in the previous chapter. It begins with the importance of renewable fuels for a sustainable environment, discussed in section 2.1. The following section 2.2 briefly illustrates a typical ignition mechanism in an SI engine and its governing parameters. Section 2.3 draws a correlation between ignitability and stability of combustion in an SI operation. The succeeding section 2.4 reviews about a variety of ignition systems, their limitations for application in the automobile sector, and a wrap up of requirements for a *'Perfect Ignition System'*. Finally, a summary of findings is presented in Section 2.5.

2.1 Alternative & Renewable Fuels – A Potential to Drive Future towards Sustainability

Internal Combustion Engines (ICE) are the most widespread energy converter in the heavy-duty transport sector. However, with the rise in CO_2 emissions in the environment, partly due to the burning of fossil fuels in combustion engines, has led to think of moving towards more carbon neutral transport in the future. The relevance of this issue is evident since the transportation sector was responsible of about 20% of the GHG emissions in EU-28 during 2014 [1]. Several alternative transport solutions such as electric automobiles & fuel cell vehicles have already been introduced in the market. However, combustion engines cannot be fully replaced yet due to several limitations, for instance, lack of presence of proper infrastructures, short driving range, high TCO, etc. [21]

The use of renewable fuels is one alternative solution which requires little or no modifications on the present-day combustion engines and has the potential to drive towards sustainable future. Liquid fuels such as alcohols and especially Ethanol (produced from sugarcane) have more than a century long history as fuels in combustion engines [2]. The high-octane ratings of alcohols make them less prone to engine knock or pre-ignition and they are therefore well suited as SI engine fuels [2]. On the other hand, Fatty-acid methyl ester (FAME) made from vegetable oils and animal fats, also known as biodiesel, have been used in engines for a long time. Since it possesses similar properties to that of conventional diesel fuel, therefore these types of renewable fuels can be used in modern diesel engines.

Alongside liquid fuels, internal combustion engines running on Natural gas[4], are also beneficial for a sustainable environment. CNG is primarily composed of methane along with some components of ethane, propane, nitrogen, and CO_2. CNG offers comparatively lower GHG compared to other hydrocarbon fuels due to its low Carbon-to-Hydrogen ratio. Furthermore, CNG is favourably combusted in SI engines as both stoichiometric and lean fuel-air mixture, taking advantage of the high knock-resisting properties of methane (high octane number) without utilizing a complex fuel injection system [5].

Therefore, a detailed study of Ignitability of an SI engine is essential as it primarily governs the early development of a stable flame nucleus, hence assuring robust combustion. In-order to comprehend impact of ignitability in-depth, we need to know more about the ignition mechanism in an SI engine, as discussed in the following section of the chapter.

[4] *Biogas is more preferrable to use in ICE because it is a renewable fuel.*

2.2 Typical Spark/Ignition Mechanism in an SI Engine

An exemplary SI engine operates (as shown in Figure 2) according to the following fundamental principles; Fuel and air mixture inside the cylinder (aspired during the intake stroke) is compressed during the compression stroke. The compressed charge gas is then ignited by an electrical spark at a controlled ignition timing. After a short delay, the homogeneous charge of fuel and air burns from the spark plug out to the cylinder walls through flame propagation [2].

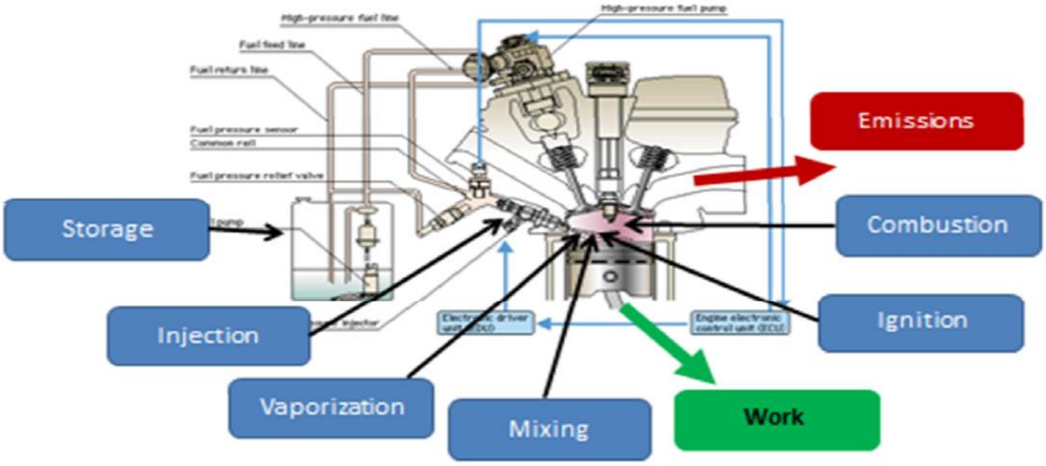


Figure 2: *A Typical Energy Conversion Process of an SI Engine [3]*

The spark ignition event of an SI engine operation can be illustrated (as shown in Figure 3) as three distinctive phases: Breakdown; Arc; and Glow. The breakdown phase consists of the formation of a conductive plasma channel and is characterized by short timescales (tens of nanoseconds) and voltages on the order of 1-10 kV or more required to initiate breakdown of the gas [7]. The start of combustion is triggered by the spark breakdown which takes place between the electrodes of the spark plug after the ignition pulse has been applied [6]. The temperature of the plasma at the breakdown reaches up to 60.000 K. Following the breakdown, arc phase is characterized by a highly conductive thin medium of plasma where gas along with electron temperatures are in thermal composure and the temperature drops down to below 10.000 K.

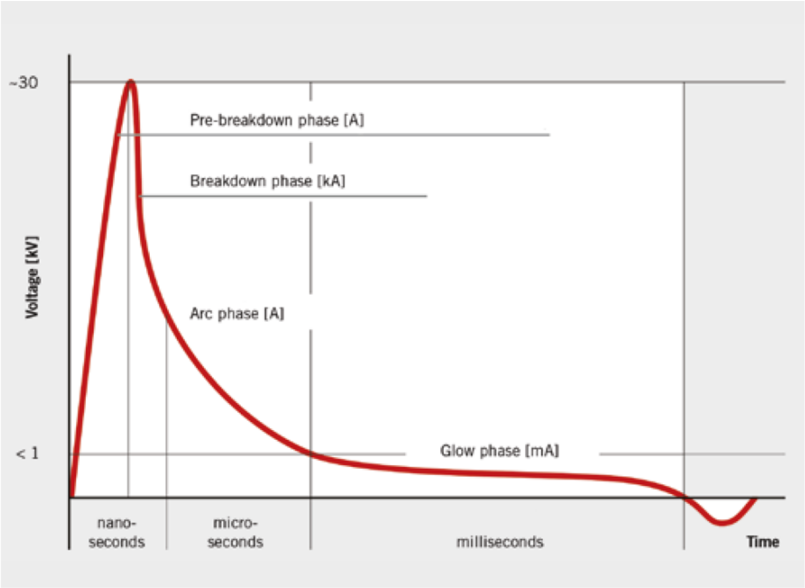


Figure 3: *A Schematic Representation of Three Distinctive Phases of Spark Discharge [13]*

Due to convection processes of the expanding hot plasma in the spark channel the neighbourhood of the gas/fuel mixture is heated up, where the first radicals are formed that are triggering the start of combustion, the so-called flame initiation [6]. The following laminar flame speed is determined by its local A/F mixture composition and its temperature, governing the flame kernel development. When the size of the flame kernel arrives at a size of approximately a few millimetres, the mean flow inside the combustion chamber along with the turbulent intensity dictates the flame propagation, and thereby major part of the succeeding combustion phase.

2.3 Ignitability vs Stability of Combustion in an SI Operation

Combustion stability is a crucial factor that influences the overall engine performances. It is usually determined by the Coefficient of Variance of Indicated Mean Effective Pressure (COV_{IMEP}) which is defined as the standard deviation of the IMEP divided by the average for a determined number of cycles [14].

$$\therefore COV_{IMEP} = \sigma_{IMEP} / \bar{x}_{IMEP}$$

Higher percentage of COV_{IMEP} brings serious problems to engine operations, for instance, decreased efficiency and fuel economy, noise, vibrations, and harshness (NVH), which is not desirable.

The formation of spark, on the other hand, plays an important role in ignitability of a fuel-air mixture, hence governing combustion. It primarily depends on the following factors:

i) **G**ap between the electrodes: The volume of spark can be elevated by increasing the gap between the electrodes [17]. As a result, the probability to trigger a self-sustained combustion enhances as well. However, with the increase in electrodes' gap (as shown in Figure 4), the required breakdown voltage will also increase.

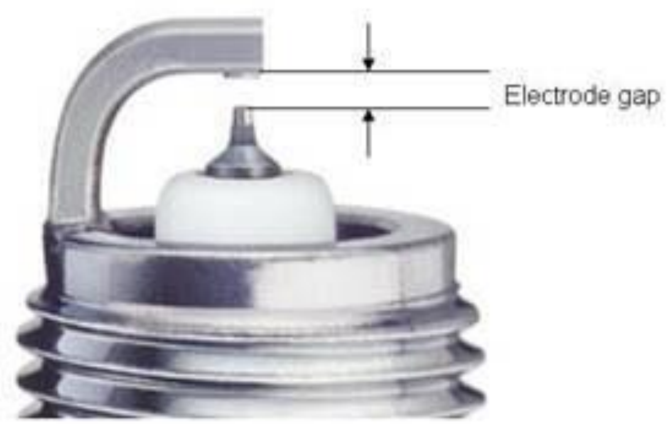


Figure 4: *A Classical Representation of a Gap between the Sparkplug Electrodes of an SI Engine*

As the gap further increases and sharp geometric features of the spark plug electrodes are worn out, higher voltages are required to initiate the spark breakdown [7]. At a certain point, the ignition coil may fail to deliver the required higher voltage for the breakdown phase (due to component limitation), leading to misfire, hence a rise in COV_{IMEP}.

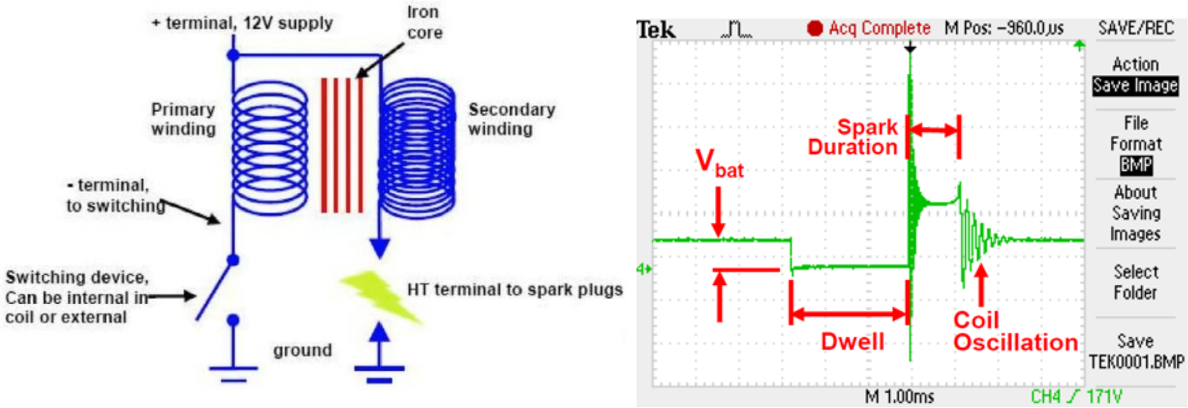
ii) **P**ressure between the electrodes' gap: With the increase in the in-cylinder pressure, the gas pressure and density between the spark plug electrodes will follow. Now, at a higher electrodes gap, the breakdown voltage requirement will be significantly enhanced at high engine loads in-order to achieve the dielectric breakdown. As an impact, occasional misfires can be noticed for some combustion cycles due to not being able to deliver sufficient breakdown voltage at the gap, hence increase in COV_{IMEP}.

Both the factors (as discussed above) are interlinked with each other and can contribute towards higher instability of combustion, hence indicating a demand for an optimized ignition system to effectively control the ignitability in-order to achieve a robust combustion.

2.4 Types of Ignition Systems

The ignition mechanism (as explained in section 1.2) is independent of the type of ignition systems used in automotive applications. Some of the widely used ignition systems are discussed below:-

2.4.1 *Inductive Discharge Ignition System*:



(5a) (5b)

Figure 5a: *Schematic Diagram of an Inductive Discharge Ignition System [18]*

Figure 5b: *Working Principle of an Inductive Discharge Ignition System*

The Inductive Discharge Ignition (IDI) System is the mostly used ignition systems in the automotive industries. As showcased in Figure 5, the ignition energy is primarily stored in the magnetic field. Here, the transistor acts as a switch. When it is "ON", a current is drawn from the battery of a vehicle through the primary winding and a magnetic field is generated. The time required to charge up the primary coil from the battery or power supply is known as the 'Dwell' time. It is directly related to the demand for the ignition power and energy to create spark and combust fuel and air mixtures at a given operating condition.

Once the transistor (acting as a switch) is turned "OFF", the rapid change in magnetic field provokes an electric voltage that is transferred to the secondary coil, thereby generating a spark on the electrodes of the sparkplug. It continues to discharge until the energy in the magnetic field is entirely drained.

2.4.2 *Capacitive Discharge Ignition System*:

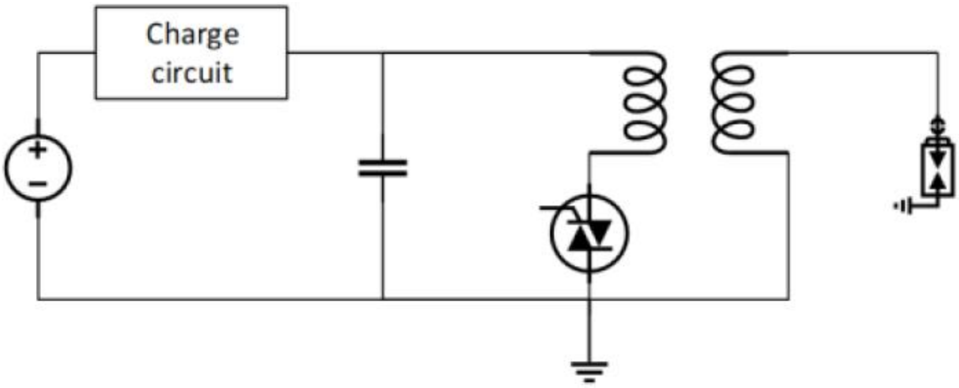


Figure 6: *Schematic Diagram of a Capacitive Discharge Ignition System [17]*

It is one of the latest ignition systems (as shown in Figure 6) available to use in automotive applications. Capacitive Discharge Ignition (CDI) system uses capacitance(s) to store the energy prior to the release of spark – as indicated by its name [17]. Once the capacitor is charged and a triggering signal is sent, the Silicon Controlled Rectifier or SCR (acting as a switch) is turned "ON", and the charge is emptied through the primary coil. As an impact, magnetic fluxes are developed in the primary coil which then generates an EMF in the secondary coil, giving rise to a very high voltage to create spark in the combustion chamber.

***Advantages & Limitations of Different Ignition Systems*:**

IGNITION SYSTEMS	ADVANTAGES	LIMITATIONS
Capacitive Discharge Ignition (CDI) System	**a)** The available spark power is higher as compared to an inductive ignition system. **b)** It has higher degrees of freedom to regulate the ignition energy by means of controlling the charging and discharging of capacitance(s) within the system.	**i)** Spark duration is shorter than in an IDI system, thereby making it difficult for lean or diluted (by means of EGR) fuel-air mixtures to ignite properly. **ii)** The cost is comparatively higher than the inductive ignition system.

IGNITION SYSTEMS	ADVANTAGES	LIMITATIONS
Inductive Discharge Ignition (IDI) System	**a)** Ignition system is more robust i.e., availability of higher spark energy (by enhanced duration of spark) at every operating condition. **b)** Low Cost.	**i)** Availability of spark current is low, which in turn, results in lower spark power [17]. **ii)** Only "Dwell" time can be controlled that governs all the spark parameters to initiate the combustion. **iii)** With the increase in spark voltage demand for the breakdown of charged gases, spark duration increases, leading to excessive wear on the spark plug electrodes.

Besides, a further rise in demand to minimize fuel consumption while operating in extreme weather conditions has led both manufacturers and researchers to develop state-of-the-art ignition systems capable of discharging even higher spark energy. To begin with, the *Multi-Charge Ignition system* is one of its latest. It comes with multiple ignition events taking place within every cycle of combustion, followed by recharge period in between, after the 1st spark discharge. With this ignition system, better combustion stability can be achieved, and the duration of the spark discharge can be varied up to 20 milliseconds, which is highly beneficial for cold starting of an engine [10]. Next to it, is *Laser Ignition System*, which provides faster combustion duration and a reduction in COV_{IMEP}, especially at higher Lambda, as compared to a conventional IDI system [11]. However, it is not suitable for automotive applications due to its high susceptibility to engine vibrations.

In addition, one of the highly advanced ignition systems is the *Corona Ignition System*. The generation of multiple flame kernels at the same time during every spark event, results in faster initial flame development and better stability of the flame [12]. However, further investigations on this ignition system (at different operating points) are required before its use in the automotive applications in the near future.

Therefore, a wrap up of requirements for a ***'Perfect Ignition System'*** are portrayed below:-

✓ High secondary voltage capability to initiate the initial breakdown even under high in-cylinder pressure and large distance between the electrodes (worn out plugs) [10].
[***Note:*** *Secondary voltage refers to the voltage available at the ignition coil to generate the spark.*]

✓ An adjustable secondary current to adapt to the boundary conditions of the combustion and to minimize the spark plug wear [10].

✓ An adjustable spark duration, depending on the operating condition of the engine.

2.5 Summary of the Findings

To summarize the literature reviews that has been made in the above sections, the following conclusions can be portrayed:-

- ✓ Due to low C/H ratio, both CNG and Biogas are beneficial to use in a Spark-ignited heavy-duty engine, hence taking benefit of the high knock-resisting properties of methane.

- ✓ Ignitability study of an SI engine is of high significance in-order to identify the most influential spark parameter that primarily governs the capability of an ignition system to provide a robust ignition.

- ✓ An effective optimization of spark parameters is necessary in-order to minimize excessive waste of spark energy, hence keeping spark plug electrodes wear to a minimum. This eventually leads to a "*Perfect Ignition System*" for future transport solutions.

This research study is focussed to study the Ignitability conditions of a heavy-duty SI gas engine at different operating points (as suggested by Volvo Penta and SEM AB). The investigation has been conducted with three different ignition systems –

I. Capacitive Discharge Ignition or CDI System (standard)

[***Note:*** *This ignition system has been used as a 'Baseline' to determine the amount of EGR that can be inhaled in the combustion chamber without compromising the combustion stability or* COV_{IMEP}]

II. Inductive Discharge Ignition System (enabled to control *'Dwell'* time)

III. Capacitive Discharge Ignition or CDI System using FlexiSpark™ ICM[5]

In the following chapter, a detailed discussion on the test methodology along with the specifications of the engine testbench, and a justification of the chosen method has been discussed.

[5] *It is an advanced Ignition Control Module, developed by SEM which enables to control multiple spark parameters, for instance, available spark voltage, spark current and duration of spark.*

3. Methodology

This chapter is primarily focussed on the methodology used to test different ignition systems (as discussed in the previous chapter) at multiple engine operating conditions. In order to provide a better clarity on the experiments conducted, a complete specification of the engine testbench along with the operating points have also been discussed.

3.1 Specifications of the Engine (used for the experiment)

This study incorporates the use of a Volvo SI heavy-duty gas engine, with all its specifications depicted in Table 1. It is operated at different engine operating conditions and multiple spark discharge parameters were measured, for instance, available spark voltage, spark current and duration of spark. In order to study the effects of ignitability on engine performances, certain parameters and performance measures were also taken into consideration, for instance, in-cylinder pressure, COV_{IMEP}, CA_{50} MFB etc. All other measurements considered during experiments have been briefly discussed (attached in Appendix I).

Table 1: *Specifications of the Volvo Gas Engine used in the Experiment*

No. of Cylinders	6
Fuel Type	CNG
Injection Type	Port Injected
Arrangement	Inline
Bore	131 mm
Stroke	158 mm
Length of Connecting Rod	267.5 mm
Compression Ratio	12.4:1
A/F Ratio	Stoichiometric (Lambda = 1)
Displacement Volume	12.8 litres
Maximum Power	330 KW
Maximum Torque	2200 Nm

3.2 Experimental Approach

All the experiments were carried out at multiple operating points of interest (as decided by the stakeholders of the project). A complete tabulation of the experimented engine operating conditions has been discussed in Table 2.

Table 2: *Engine Operating Conditions (tested)*

Operating Point	***Engine Speed (RPM)***	***Brake Torque(Nm)***	***Engine Load***
1	1000	1780	80% (approx.)
2	1500	1000	45% (approx.)
3	1000	150	06% (approx.)

All the tests were performed at normal engine operating temperature. The engine was pre-calibrated at the engine operating points using stoichiometric A/F mixture (λ = 1) with no EGR. Alongside, the spark timing was also set in accordance with the MBT, which implies CA_{50} within the range of 6-10 CAD ATDC. Furthermore, the COV_{IMEP} target ($\leq 2.5\%$) was set by Volvo Penta, based on the specification of the engine testbench, available at Lund University LTH. The ignition systems used in this study comprises of the following:

Capacitive Discharge Ignition (CDI) System: It has been used as a reference or 'Baseline' ignition system to determine the EGR limit at the engine operating points as mentioned in Table 2. At individual operating point, the experiments began with stoichiometric A/F mixture with no EGR. The engine parameters were considered to compute COV_{IMEP}, Cumulative Heat Release and Crank Angle Degrees at 50% Mass Fraction Burnt (CA_{50}). In addition, spark timing was also recorded at that condition.

Now, the experiment was proceeded by adding EGR in the intake air with an increment of 3% (by volume) while keeping an eye on both the combustion stability (COV_{IMEP}) and CA_{50}. The spark timing was also adjusted with the increase in the EGR level to ensure CA_{50} to be within the MBT region. At one point, when the $COV_{IMEP} > 2.5\%$, the level of EGR and adjusted spark timing was recorded and used as the 'Baseline' for the other ignition systems (tested). Along with EGR limit, all the spark parameters were also recorded at each operating point.

Inductive Discharge Ignition (IDI) System: Using the 'Baseline' EGR level and the Spark Advance timing for the aforesaid operating points, the IDI system was tested by varying the dwell time until the $COV_{IMEP} \geq 2.5$ %. Next to it, the dwell is further enhanced (using the datasheet provided by SEM AB)[6] and accordingly, EGR level is increased until the $COV_{IMEP} > 2.5\%$. The spark parameters were also recorded at the tested dwell times (for every engine operating point) when COV_{IMEP} was within its desired level.

[6] *Ignition coil 805 100 82 – Inductive Ignition Coil for CNG, LPG & Biogas fueled engines – SEM AB*

FlexiSpark™ *CDI System*: This system, equipped with a FlexiSpark™ module, provided higher degrees of freedom to optimally design the spark while achieving robust combustion. A total of 24 different combination of spark parameters (also called spark modes), were available for the experiments (as shown in Appendix II).

Using the 'Baseline' EGR level and Spark Advance timing as a reference, all the spark modes were tested to identify the minimum spark energy required w.r.t EGR increment on every engine operating point (tested). The EGR limit was determined by taking COV_{IMEP} into account with a target of $\leq 2.5\%$.

Note: *For all the tested ignition systems, a new spark plug (0.3 mm gap between center and ground electrodes) was installed in-order to minimize the drift to be caused due to spark plug wear while testing the systems.*

3.3 Justification of the Experimental Approach

Considering the objective of the project, it was initially important to find out the reference EGR level for the engine operating points. The inherent properties of a standard CDI system (high spark power with short spark duration) with no control over the spark parameters make it difficult to initiate a stable combustion, especially at low load operations.

On the other hand, with high spark current, the probability to develop a self-sustained flame-front is enhanced at higher engine loads. Therefore, the standard CDI system has been used as a 'Baseline' to identify the amount to EGR that can be inhaled in the combustion chamber (at every engine operating point) while the COV_{IMEP} is within the desired limit. Using the reference EGR level, other two ignition systems were tested to determine the minimum spark power and energy, right enough to trigger a robust combustion.

In case of IDI system, the degrees of freedom to control spark was limited to 'dwell or coil-charging' time. Hence, it was adjusted w.r.t EGR increment to identify the minimum spark duration necessary to initiate a self-sustained reaction process.

Finally, with higher control over spark discharge parameters, the FlexiSpark™ CDI system was tested by effectively varying the parameters at every engine operating point (tested). This paved the way to identify the optimal spark power and energy required to combust the charged gases w.r.t EGR increment.

In the following chapter, all the experimental results and analysis will be discussed in detail after post-processing of the data collected from both the engine testbench and the ignition measurement setups.

4. Results

This chapter is intended to discuss about the results and analysis made from the experimental data for the three different ignition systems tested at every engine operating point, as described in the previous chapter. Finally, the ignition systems have been compared w.r.t the engine performances and spark discharge parameters in-order to identify the best suitable ignition system.

4.1 Parameters considered for Engine Performance Analysis

In-cylinder pressure traces of 200 cycles have been used in-order to comprehend the engine performances at every engine operating point, using different ignition systems. The parameters that were considered are addressed below:-

a. Indicated Mean Effective Pressure – IMEP (Bar)

b. Co-efficient of Variance of IMEP - COV_{IMEP} of 200 cycles (%)

c. Heat Release Rate – HRR (Joules/CAD)

$$\frac{dQ}{d\theta} = \frac{\gamma}{\gamma - 1} p \frac{dV}{d\theta} + \frac{1}{\gamma - 1} V \frac{dp}{d\theta} \quad [19]$$

d. Cumulative Heat Release (Joules)

e. Initial Flame Development Time – $CA_{SA\text{-}10}$ MFB (CAD)

f. Burn Duration – $CA_{10\text{-}50}$ MFB (CAD)

g. Combustion Duration - $CA_{10\text{-}90}$ MFB (CAD)

h. Brake Specific Fuel Consumption (gms/kw-hr)

i. Engine-out Hydrocarbon (C3) Emissions – THC (PPM)

4.2 Parameters considered for Ignition Systems Performance Analysis

The parameters that were considered to compare the performances of the tested ignition systems are given below:-

i. Spark Voltage (Kilovolts)

ii. Spark Current (Milliamperes)

iii. Spark Duration (Microseconds)

iv. Spark Power (Joules/Second)

$$\therefore \mathbf{S_{POWER}} = (\text{Spark Voltage} * \text{Spark Current})$$

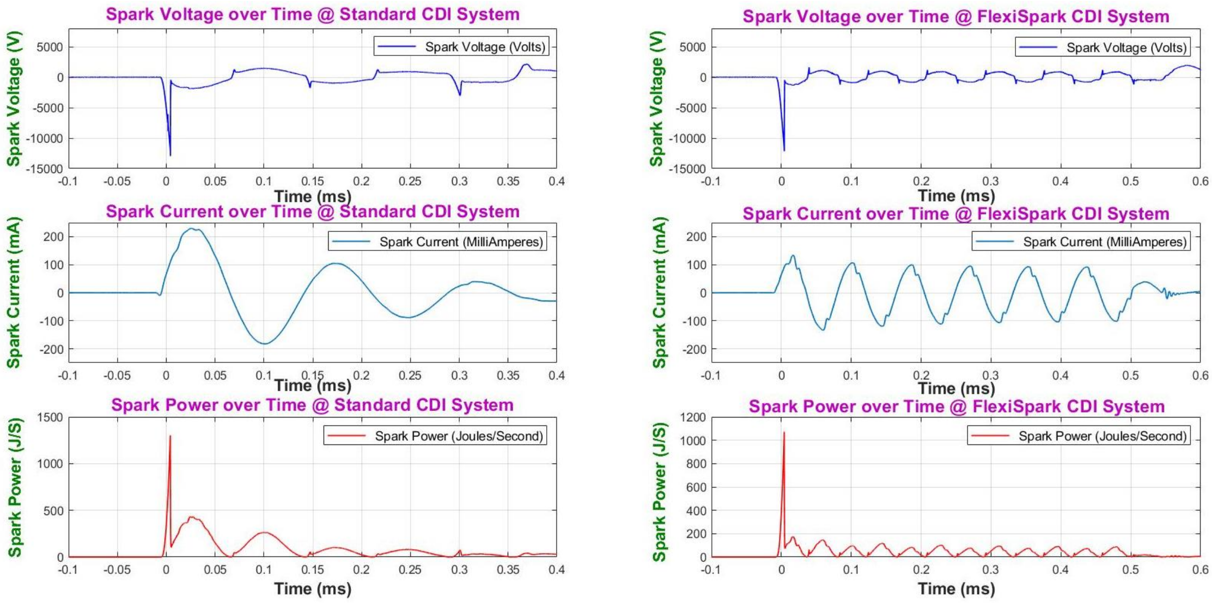


Figure 7: *Waveforms of Spark Voltage, Current and Power of both Standard and FlexiSpark™ CDI System*

It can be seen from Figure 7 that spark voltage (after the breakdown) remains in almost steady-state condition throughout the spark duration for both Standard CDI and FlexiSpark™ CDI system[7]. It is the spark current that influences spark power, as shown in Figure 7. Therefore, spark current is treated as the governing parameter of spark power while comparing performances of all the tested ignition systems.

v. Spark Energy (Millijoules)

$$\therefore S_{ENERGY} = \int_{t0}^{t} Spark\ Power \quad [\text{where } t_0 = \text{start of spark and } t = \text{end of Spark}]$$

[7] *Similarly, the spark power of an **Inductive Discharge Ignition System** is governed by Spark current. A typical spark voltage and current waveform (from a research paper) is attached in the Appendix II.*

4.3 Engine Performance Analysis @1000 RPM and 1780 Nm

4.3.1 Standard Capacitive Discharge Ignition (CDI) System

As discussed in the previous chapter, the experiment was performed by increasing the EGR level from 0-12 % (increment of 3% in each step). Accordingly, the Spark timing was also adjusted to achieve MBT. It was observed that with the increase in EGR, the cycle-to-cycle variation in the IMEP increased. On the other hand, combustion speed gradually degraded while THC emissions elevated with the addition of EGR, as shown in Figure 8.

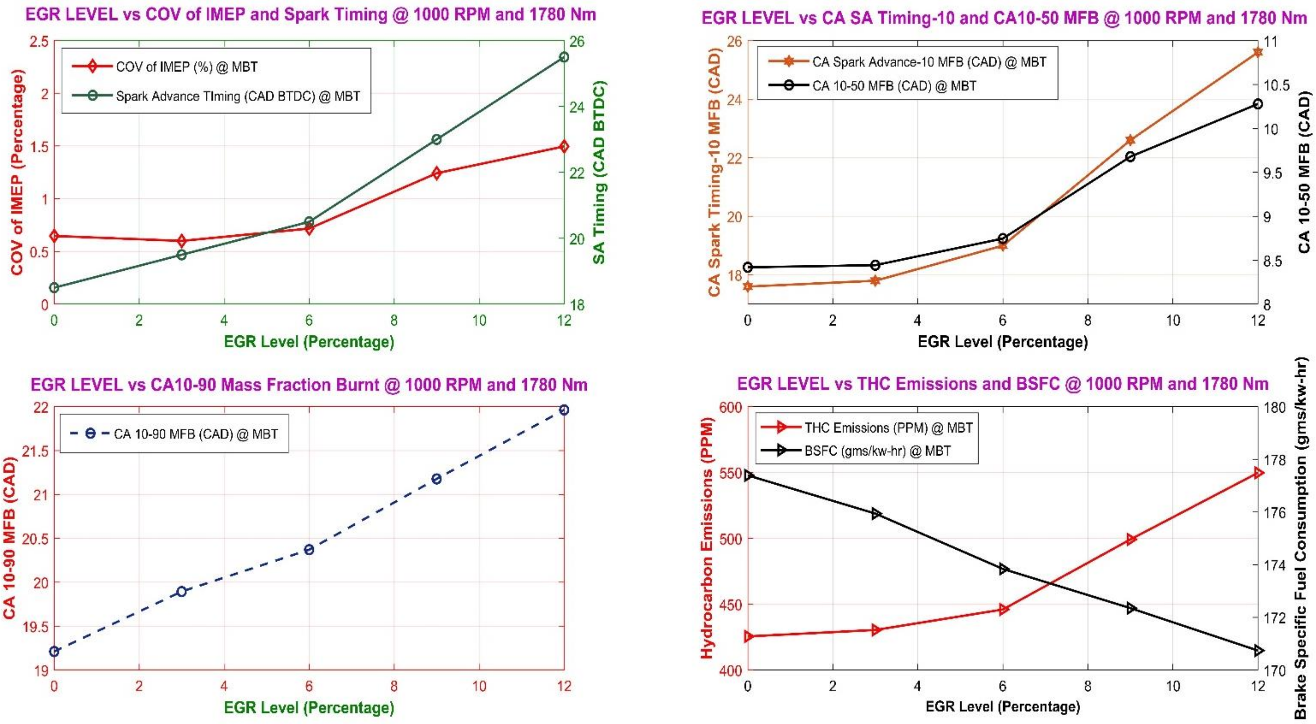


Figure 8: *Standard CDI - EGR Level vs Engine Performance Parameters @ 1000 RPM and 1780 Nm*

Therefore, it is understood from the results that the variation in the amount of dilution with charged gas near the spark plug gap enhanced with the increase in EGR, giving rise to COV_{IMEP}. Furthermore, the reaction rate decreased with the addition of EGR due to presence of higher dilution in the combustion chamber. As an impact, it became more challenging to trigger a self-sustained combustion and therefore, an enhancement in both flame development time and main combustion duration was noticed with the increase in EGR.

4.3.2 Conventional Inductive Discharge Ignition (IDI) System

The experiment with this ignition system was performed by varying the dilution level along with the dwell time from 1.54 ms to 3.38 ms (using datasheet provided by SEM AB)[8]. Accordingly, the Spark timing was also adjusted to achieve MBT. Figure 9 gives an overview of the minimum charging (dwell) time required to initiate combustion w.r.t EGR increment.

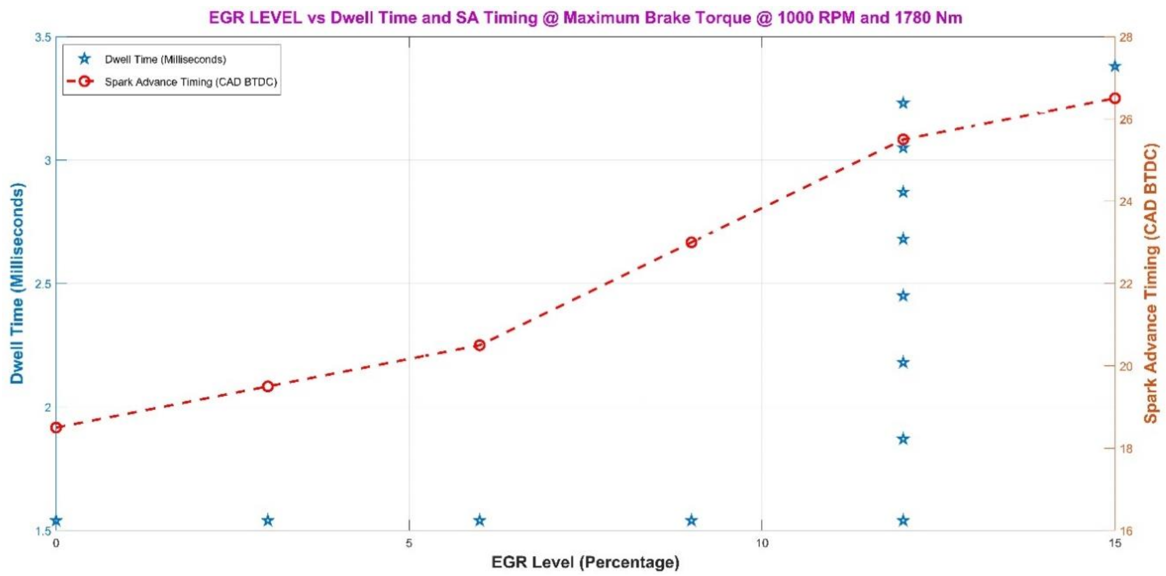


Figure 9: *IDI - EGR Level vs Dwell Time and SA Timing @ 1000 RPM and 1780 Nm*

It can be noticed that multiple dwell times were tested at 12% EGR to see if further addition of EGR was possible with increase in dwell time. However, it was found that the increment of EGR to 15% was achievable at dwell time above 3.3 ms.

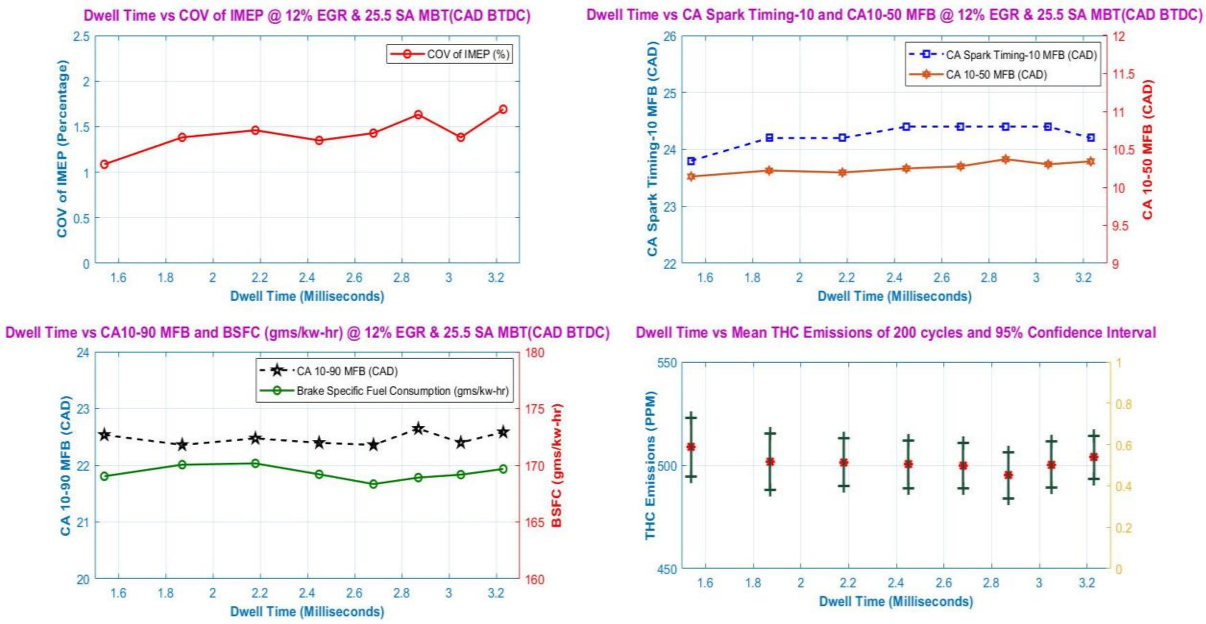


Figure 10: *IDI - Dwell Time vs Engine Performance Parameters at 12% EGR @ 1000 RPM and 1780 Nm*

[8] *Ignition coil 805 100 82 – Inductive Ignition Coil for CNG, LPG & Biogas fueled engines – SEM AB*

Therefore, a further analysis was performed at 12% EGR (as shown in Figure 10) in-order to identify an optimal dwell time to be used while assuring higher combustion stability. However, after reviewing multiple combustion parameters, no significant progression in engine performances was observed with the enhancement increase in dwell time. This gives a clear indication that once a self-sustained flame has developed, there is no need to add excess energy at the spark as it becomes a waste.

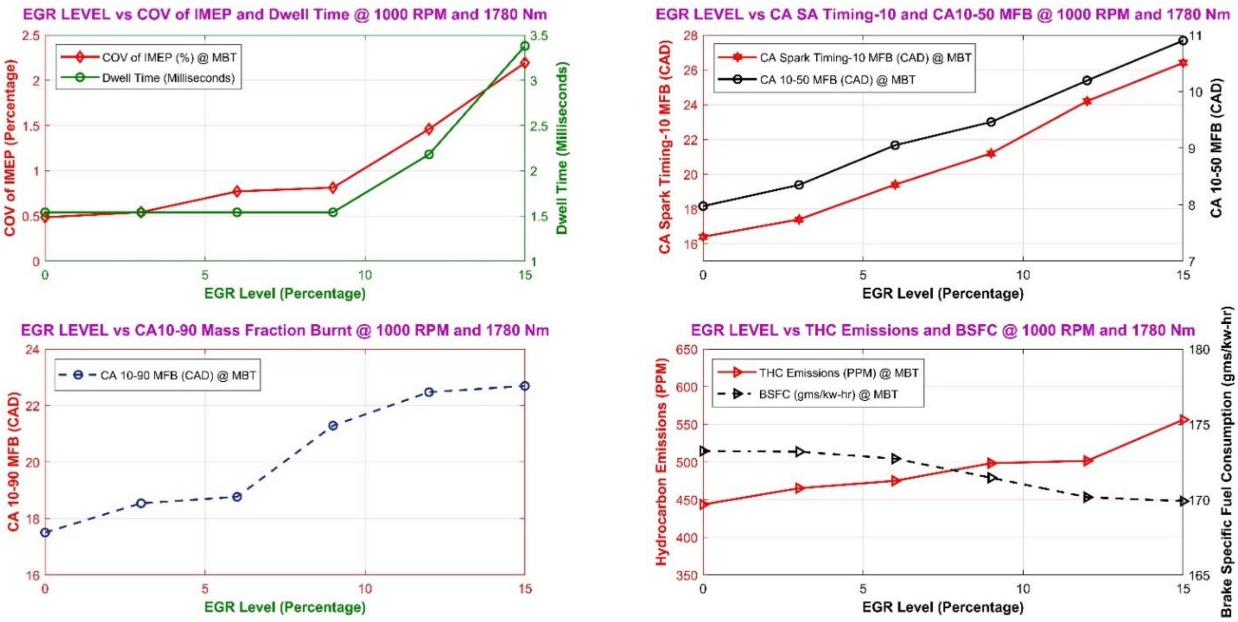


Figure 11: *IDI - EGR Level vs Dwell Time (set) and Overall Engine Performances @ 1000 RPM and 1780 Nm*

Figure 11 provides a complete map of combustion performance parameters w.r.t dilution level increment. It was found that the combustion stability was degraded with the increase in EGR, giving a rise in COV_{IMEP}. One possible reason could be an increase in dilution level near the sparkplug gap, hence the probability to hit a favourable fuel-air mixture decreased with the addition of EGR.

4.3.3 *Advanced CDI System using FlexiSpark^{TM} ICM*

The experiment was conducted by varying the EGR from 0-12% (by vol.) with an increment of 3%, and accordingly 24 spark modes were tested to identify the most favorable mode to use at every dilution level (tested). Figure 12 provides information on minumum spark energy requirement to trigger combustion with the increment in the EGR level, while running the engine at 1000 RPM with 1780 Nm.

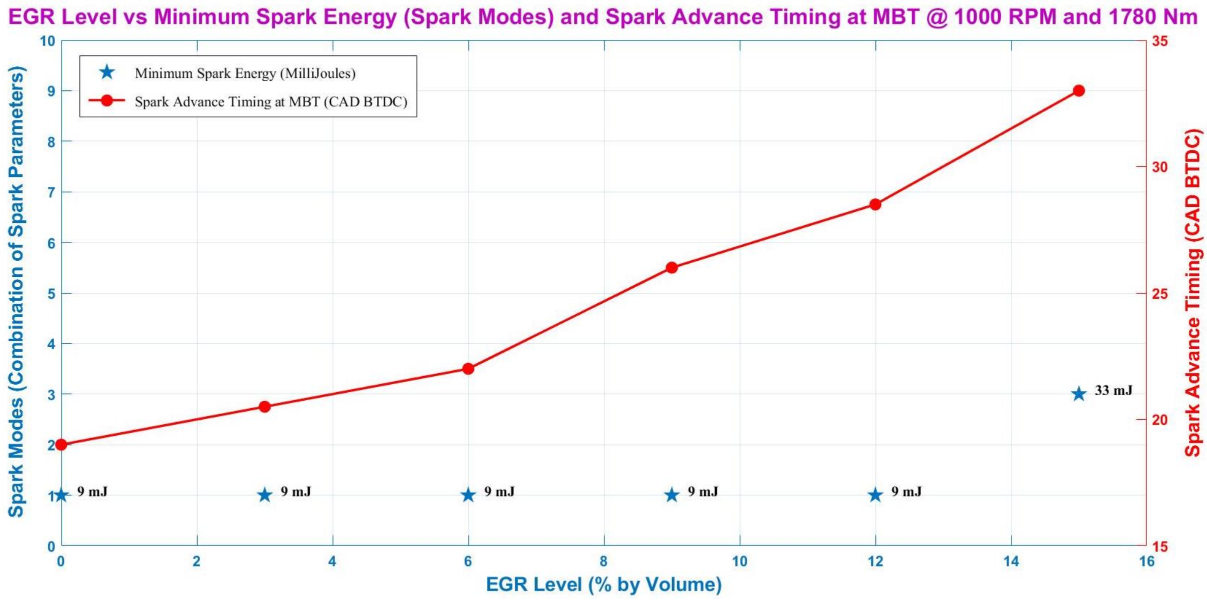


Figure 12: *FlexiSpark^{TM} CDI - EGR Level vs Spark Modes and SA Timing @ 1000 RPM and 1780 Nm*

In-order to review whether the combustion process improves with the increase in spark power and/or energy, multiple spark modes were tested at 12% dilution. An in-depth analysis on the engine performances were further conducted, as shown in Figure 13.

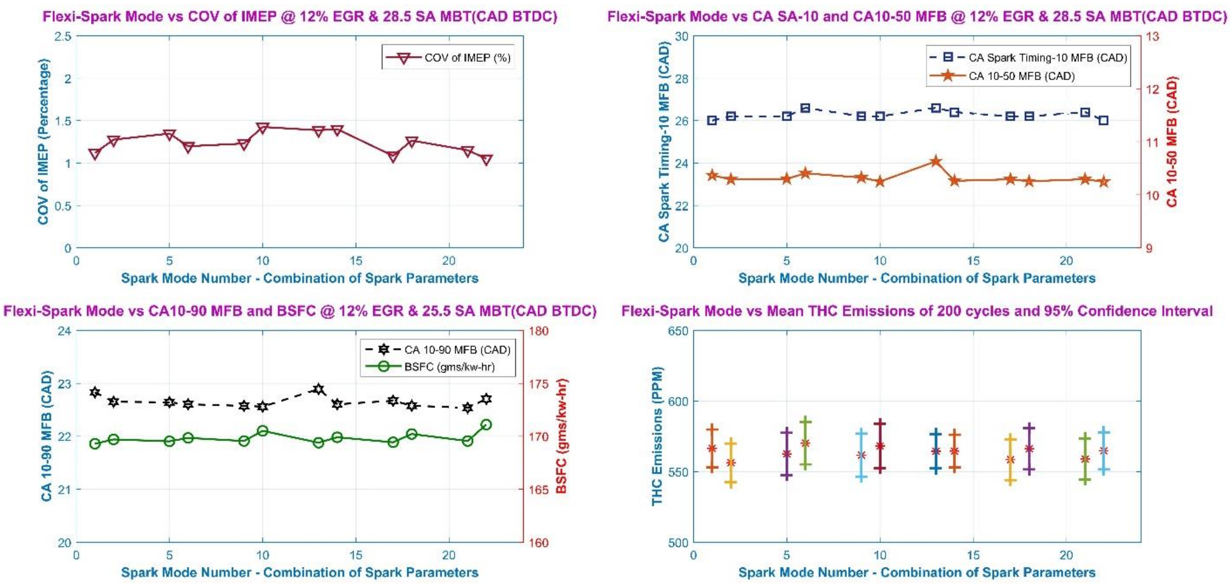


Figure 13: *FlexiSpark^{TM} CDI - Spark Modes vs Engine Performance at 12% EGR @ 1000 RPM and 1780 Nm*

However, no significant enhancement in combustion was observed with the increase in spark power and/or energy (spark modes). Therefore, it is comprehended that once the main combustion process starts, there is nothing to gain with further addition of spark power and/or energy.

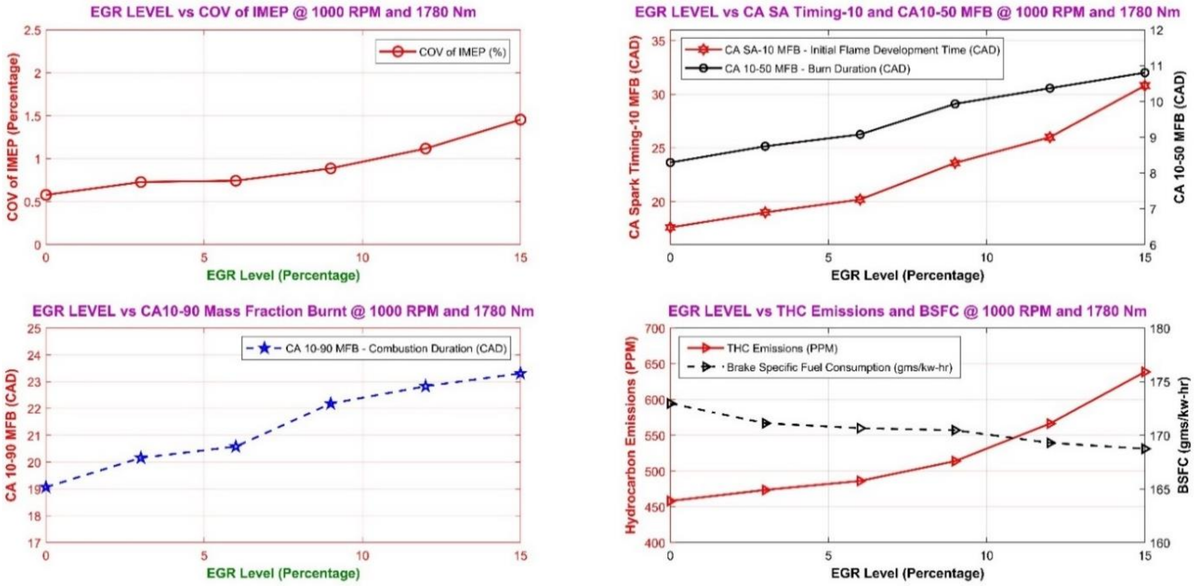


Figure 14: *FlexiSpark^{TM} CDI - EGR Level vs Engine Performance Parameters @ 1000 RPM and 1780 Nm*

Hence, Figure 14 gives a picture of overall engine performances with the increment in the EGR level when using FlexiSpark^{TM} CDI system as an ignition source. Total Hydrocarbon emissions tend to rise with the addition of EGR beyond 12% due to high concentration of CO_2 in the combustion chamber, resulting in earlier flame quenching.

4.4 Engine Performance Analysis @1500 RPM and 1000 Nm

4.4.1 Standard Capacitive Discharge Ignition (CDI) System

The experiment at this EOP was performed in a similar way, as discussed before. It can be seen in Figure 15 that the engine could be operated with higher dilution, even with shorter spark duration. However, when running at 15% EGR content, it is observed the quality of combustion degraded with no further improvement in brake specific fuel consumption noticed.

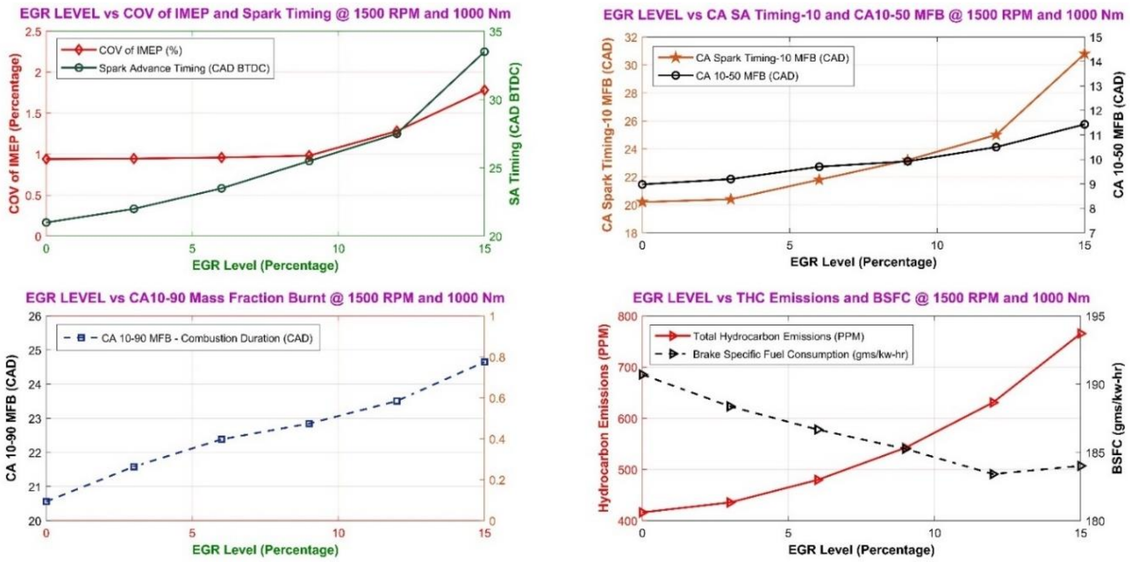


Figure 15: *Standard CDI - EGR Level vs Engine Performance Parameters @ 1500 RPM and 1000 Nm*

4.4.2 Conventional Inductive Discharge Ignition (IDI) System

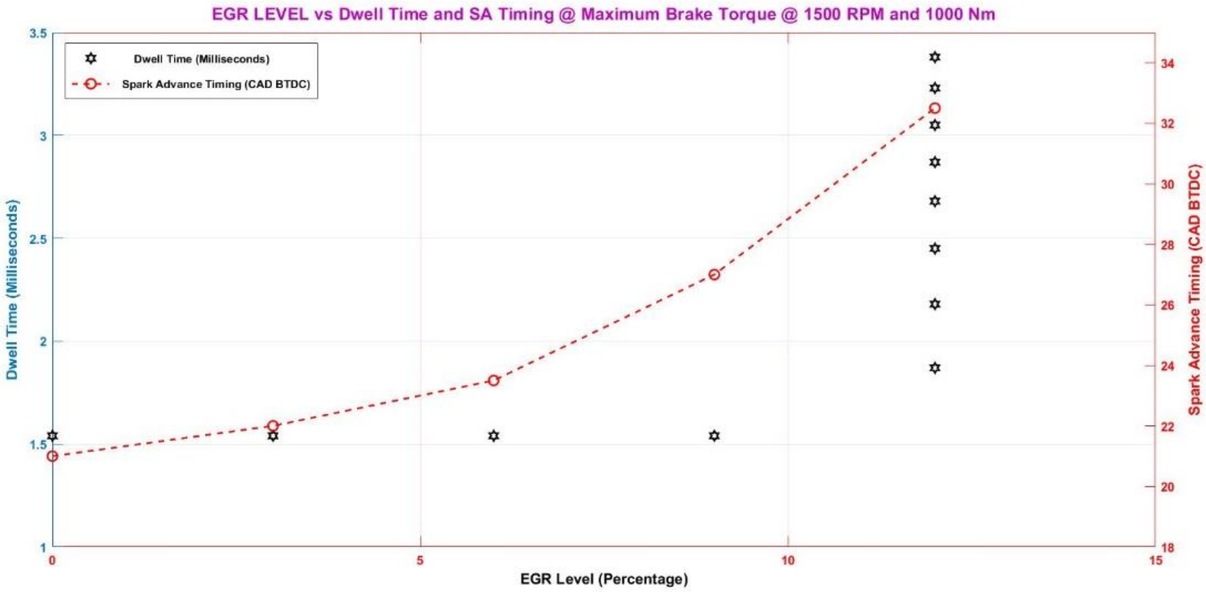


Figure 16: *IDI - EGR Level vs Dwell Time and SA Timing @ 1500 RPM and 1000 Nm*

Figure 16 discusses about the experiment performed using conventional IDI system at 1500 RPM with 1000 Nm Torque. The maximum dilution (EGR) possible with this ignition system was 12% by vol. Surprisingly, further increment of EGR could not be possible, even when maximum allowable dwell time (~ 3.38 ms) was set to charge the coil.

Since multiple dwell times were used at 12% dilution level, a further analysis was necessary, in-order to identify minimum charging time of the coil while assuring robust combustion.

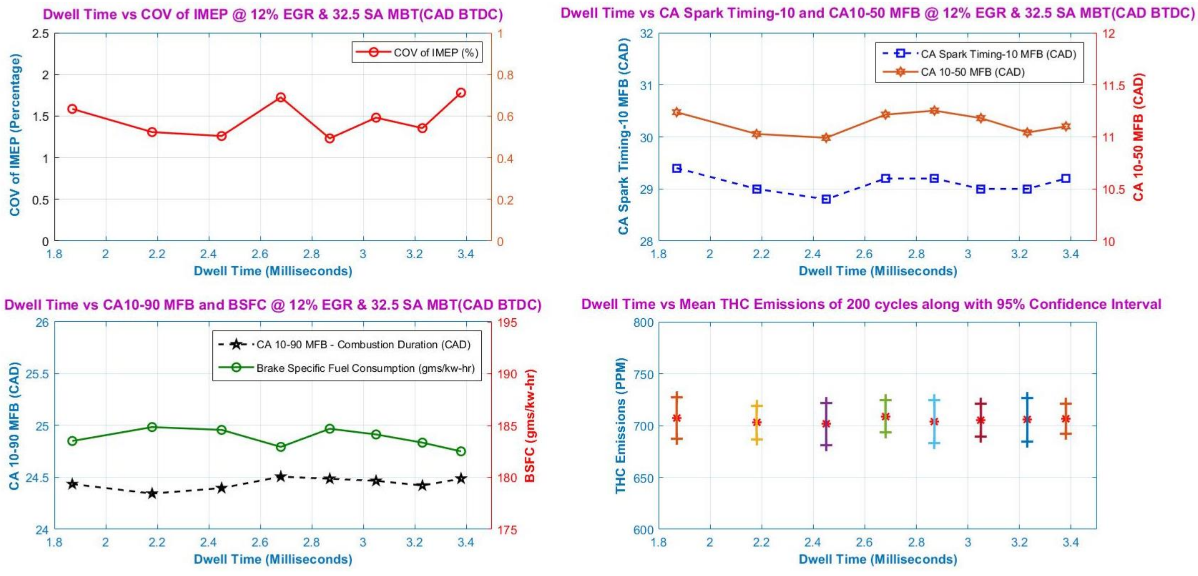


Figure 17: IDI - Dwell Time vs Engine Performance Parameters at 12% EGR @ 1500 RPM and 1000 Nm

However, no significant variation in engine performances was noticed w.r.t increase in dwell time, as shown in Figure 17. Hence it again indicates that once the sufficient energy is provided to trigger the combustion, the excess energy becomes a waste.

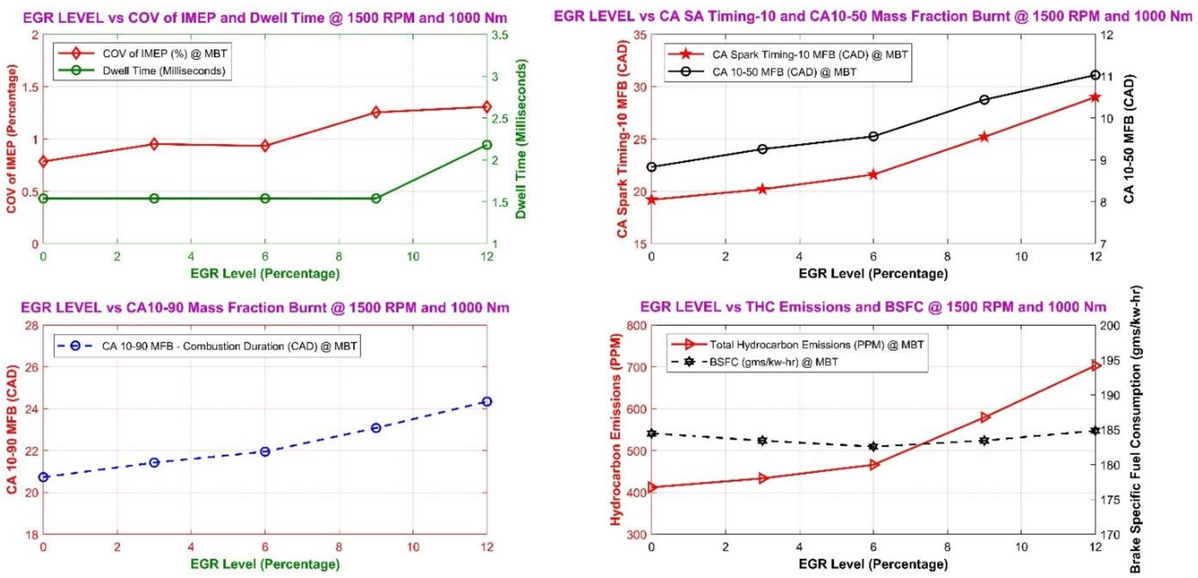


Figure 18: IDI - EGR Level vs Dwell Time (set) and Overall Engine Performances @ 1500 RPM and 1000 Nm

Figure 18 showcases an outright of the engine performances with the increase in dilution level (EGR). It was again noticed that the flame development time increased with the addition of EGR, leading to a decrement in combustion speed. Hence, an elevation in main combustion duration (CA_{10-90}) was also observed with the EGR increment.

4.4.3 Advanced CDI System using FlexiSpark™ ICM

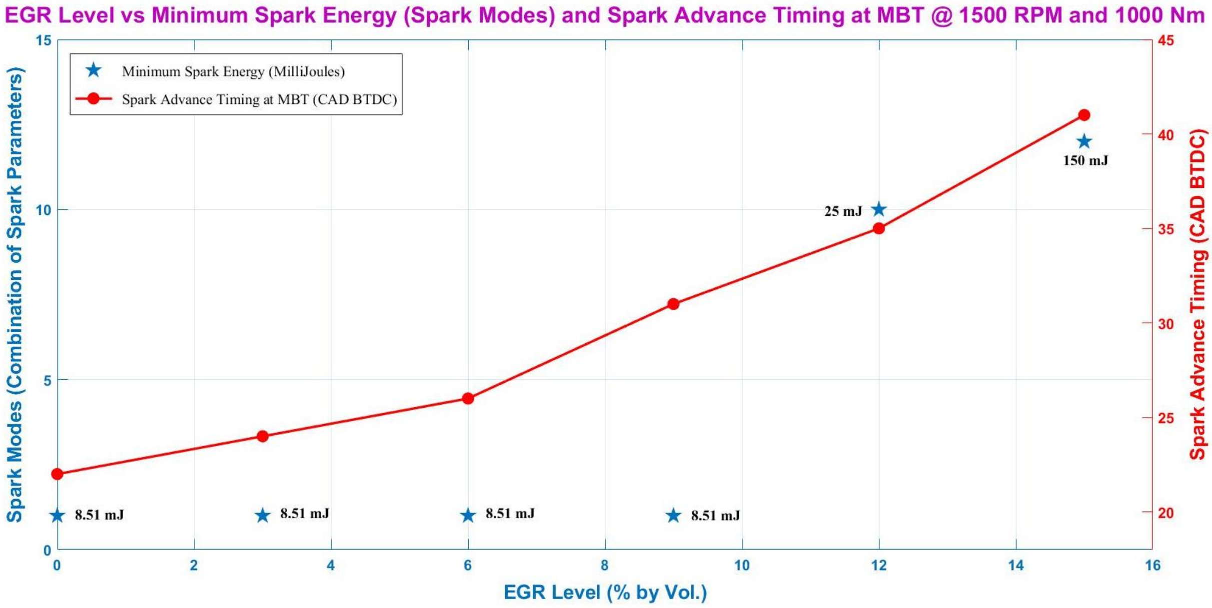


Figure 19: *FlexiSpark™ CDI - EGR Level vs Spark Modes and SA Timing @ 1500 RPM and 1000 Nm*

Figure 19 gives an overview of the experiments performed using FlexiSpark™ ICM (by varying the spark parameters). It can be seen that the minimum energy required to develop the flame front is ~ 8.5 mJ, even with 9% EGR (by vol.). However, when further dilution was added in the combustion chamber, higher spark duration was needed to hit a favourable fuel-air mixture, thereby initiating combustion.

An interesting study was conducted (as shown in Figure 20) while reviewing the spark energy requirements at both 9% and 12% EGR, added in the combustion chamber. It was found that with the increase in the peak spark current to 50 mA more, the engine could be operated with higher dilution, while the spark duration remained unchanged (200 µS).

A proper justification could be made when comparing the spark power of the individual modes. An increment in spark current allow to discharge higher beam of electrons (over time) at the spark plug gap, influencing the power (over time) of spark. It results in an increase in flame kernel size and hence, the probability to hit the fuel-air mixtures enhance, even with higher dilution (EGR) level.

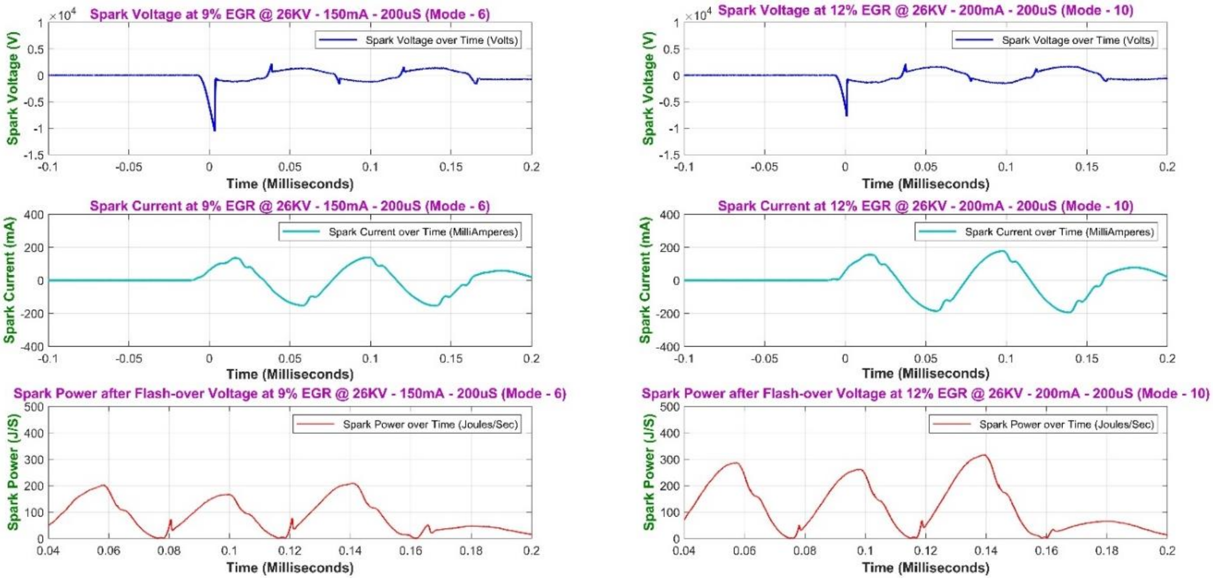


Figure 20: *FlexiSpark[TM] CDI - In-depth Analysis at Spark mode 6 and 10 @ 1500 RPM and 1000 Nm*

Finally, an overview of the engine performances w.r.t increment in the EGR level is shown in Figure 21. The COV_{IMEP} was within the limit of 2.5% for the whole range of EGR level (tested), indicating a decent stability of combustion. However, when the EGR level was further increased, occasional misfires were identified in multiple cylinders even when maximum spark power and energy was discharged at the spark plug gap.

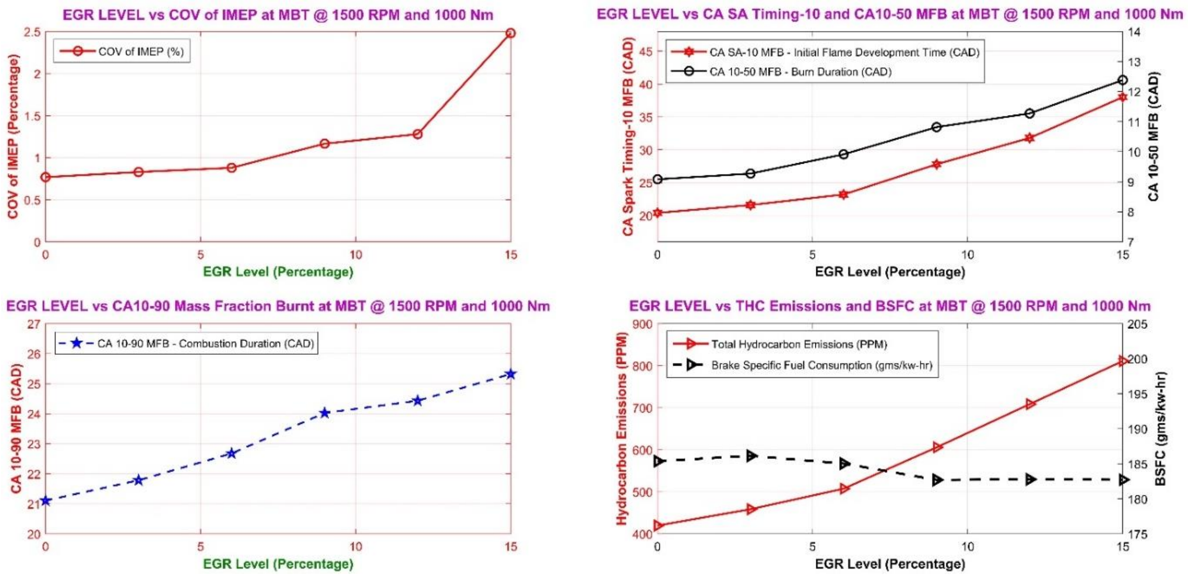


Figure 21: *FlexiSpark[TM] CDI - EGR Level vs Overall Engine Performances @ 1500 RPM and 1000 Nm*

4.5 Engine Performance Analysis @1000 RPM and 150 Nm

4.5.1 Standard Capacitive Discharge Ignition (CDI) System

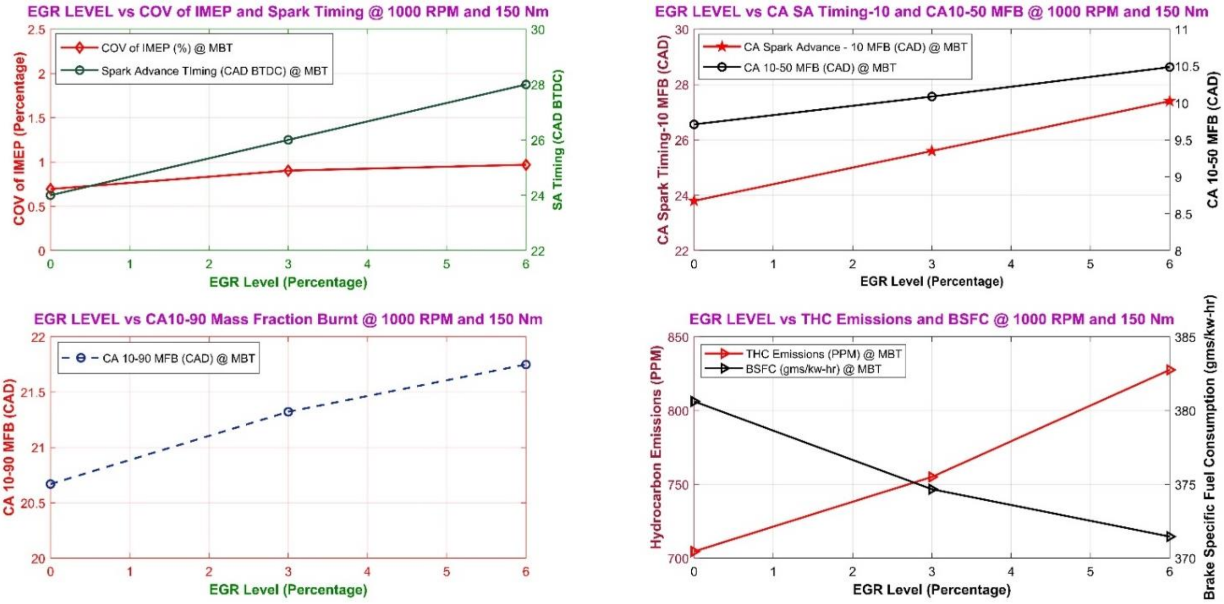


Figure 22: *Standard CDI - EGR Level vs Engine Performance Parameters @ 1000 RPM and 150 Nm*

Figure 22 gives an overview of the experiment performed with standard CDI system when running the engine at 1000 RPM with low torque (150 Nm). The maximum level of EGR introduced in the combustion chamber at this EOP was 6%, using standard CDI system . However, when further dilution was added, engine started to misfire due to extremely short spark duration.

4.5.2 Conventional Inductive Discharge Ignition (IDI) System

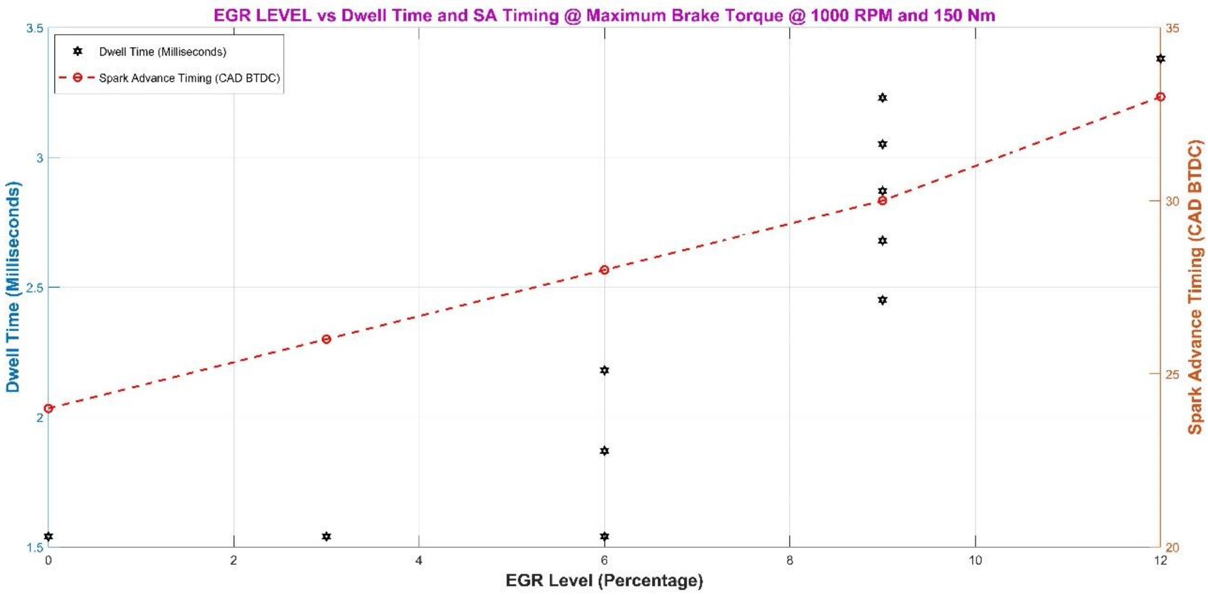


Figure 23: *IDI - EGR Level vs Dwell Time and SA Timing @ 1000 RPM and 150 Nm*

[Figure 23](#) gives an overview of the minimum charging time (dwell) required in-order to operate the engine w.r.t increment in EGR. A further investigation on engine performances was carried out at 9% EGR (as shown in [Figure 24](#)) to identify the best suitable dwell time to use in-order to achieve high combustion stability.

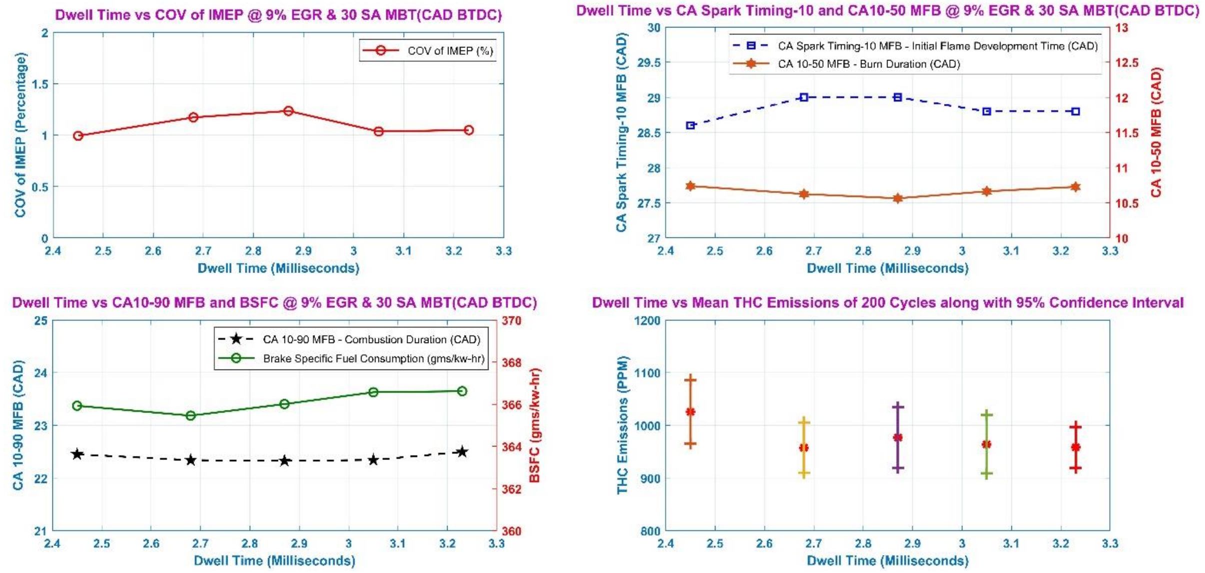


Figure 24: *IDI - Dwell Time vs Engine Performance Parameters at 9% EGR @ 1000 RPM and 150 Nm*

After in-depth analysis of different engine performance parameters w.r.t dwell time increment, no further improvement in combustion was noticed. Therefore, it is again understood that once the main combustion has initiated, there is nothing more to gain by further increasing the spark power and/or energy.

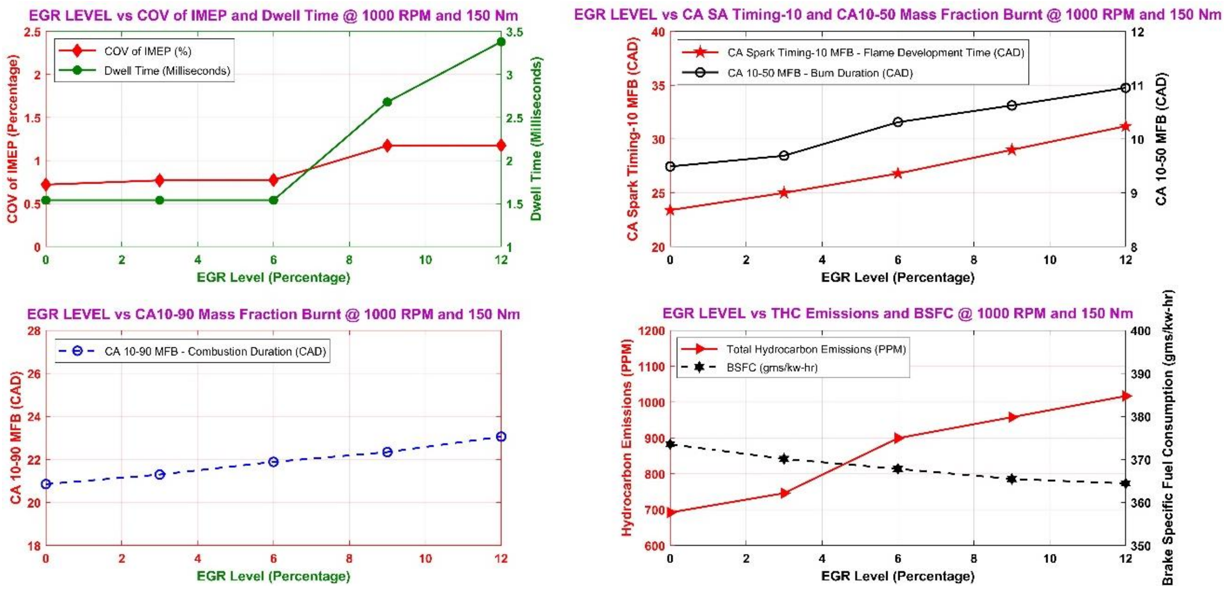


Figure 25: *IDI - EGR Level vs Dwell Time (set) and Overall Engine Performances @ 1000 RPM and 150 Nm*

Finally, an outline of engine performances along with charging time of the coil has been shown in [Figure 25](#) w.r.t EGR level increment. The stability of combustion – COV_{IMEP} was below 1.5%, even at 12% EGR.

4.5.3 Advanced CDI System using FlexiSpark™ ICM

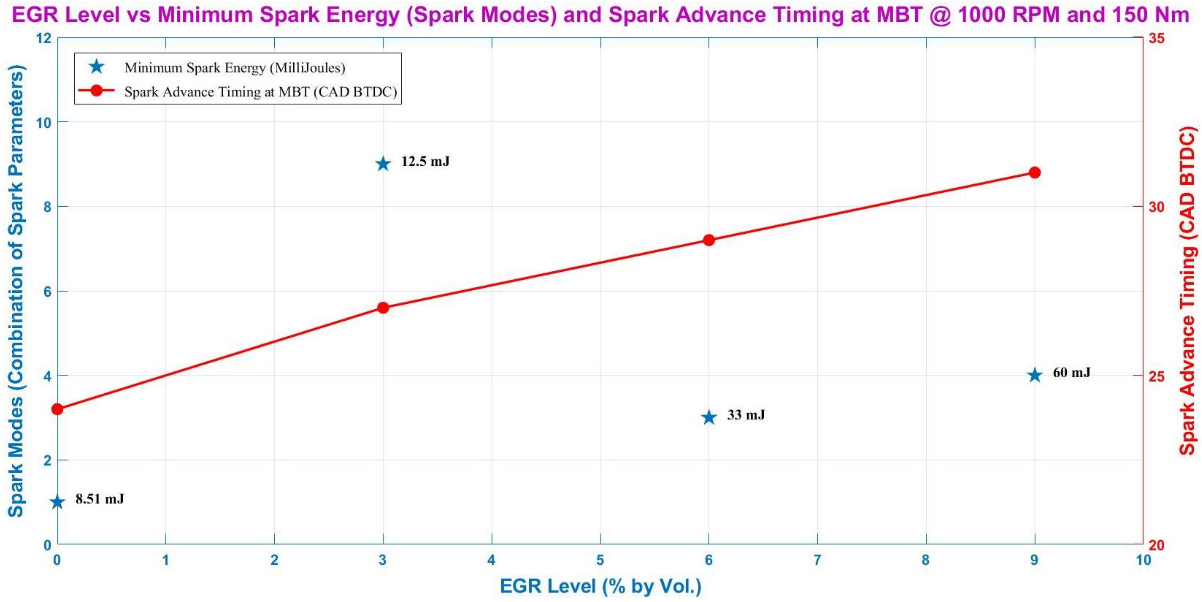


Figure 26: *FlexiSpark™ CDI - EGR Level vs Spark Modes and SA Timing @ 1000 RPM and 150 Nm*

The final experiment, as shown in Figure 26, was performed to identify the minimum energy required to trigger combustion w.r.t EGR increment, while assuring stable engine operation. It was found in the analysis that the maximum dilution achievable was 9% by vol., when using its maximum spark duration (~1 ms).

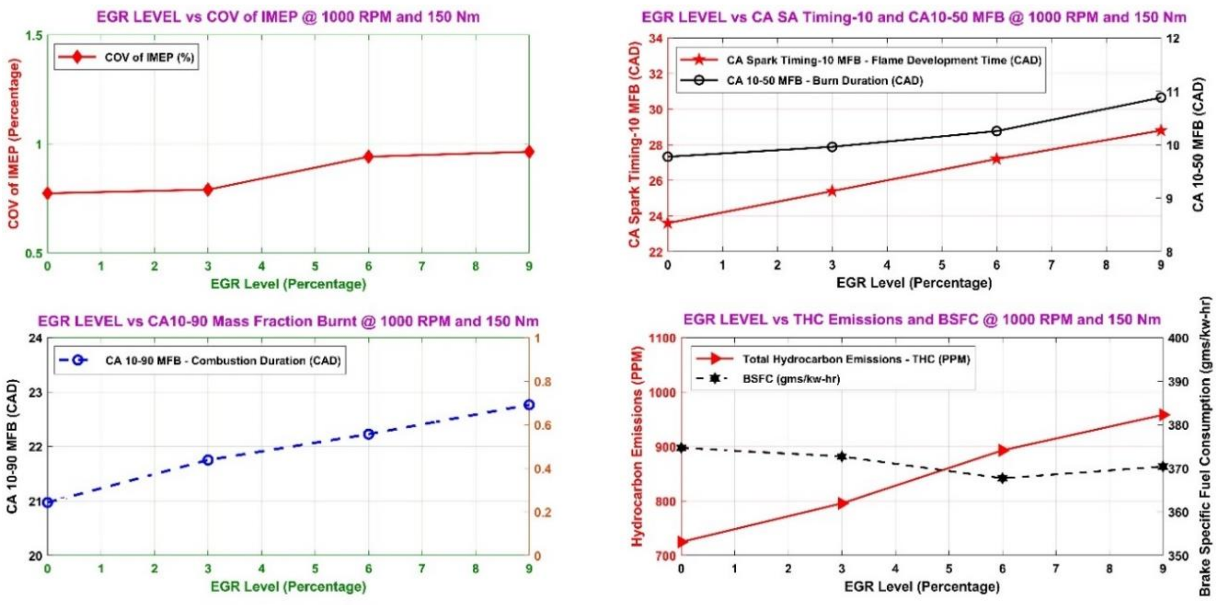


Figure 27: *FlexiSpark™ CDI - EGR Level vs Overall Engine Performances @ 1000 RPM and 150 Nm*

Finally, an overview of overall engine performances has been showcased in Figure 27 at different EGR level (tested). It can be seen that the variation in IMEP was within 1%, even when the engine was operated at higher EGR ~ 9%.

4.6 Final Comparison of Three Ignition Systems

This section is intended to compare and analyse the engine performances with respect to spark discharge parameters for the three different ignition systems. The comparison is primarily focussed to review the stability of combustion versus spark discharge parameters at the tested operating points, with the increment in EGR level. Furthermore, the combustion quality and the main combustion duration has also been correlated in-order to comprehend the effects of ignitability on combustion.

It is to be noted that the spark current[9] measured for both standard CDI and FlexiSpark™ CDI system are Alternating Current (AC). Hence, their RMS (Root Mean Square) values have been used in-order to effectively compare with the DC spark current of IDI system.

$$\therefore I_{RMS} = \sqrt{\frac{1}{N}\sum(I\text{current})^2} \qquad \text{[where N = no. of measurements]}$$

4.6.1 Comparison at 1000 RPM – 1780 Nm

Figure 28: *Comparison of Combustion Stability vs Spark Energy Discharge @ 1000 RPM and 1780 Nm*

Considering the performances of a standard CDI system (Baseline), it is capable to handle upto 12% EGR with desired combustion stability (COV_{IMEP} < 2.5%). However, when further dilution was added, the variation in IMEP escalated to more than 3%, indicating the combustion, to be unstable (as shown in Figure 28). It is understood that the probability to hit the fuel-air mixture hard enough to trigger the reaction went down with 15% EGR, due to comparatively shorter spark duration ~ 370µS (as shown in Figure 29). The results also state that the spark power, being consistently produced over time, was not enough to develop a self-sustained flame nucleus due to the presence of high dilution at the spark plug gap.

[9] *A typical spark current waveform of an AC CDI system vs DC Conventional IDI system is attached in Appendix II.*

On the other hand, the IDI system is able to achieve stable combustion with 15% EGR, however, at the cost of maximum spark energy discharge at the gap. It is comprehended that with an increase in demand for peak spark current (power) to develop a stable flame front, the IDI system charges the coil with maximum dwell time (~ 3.38ms). As an impact, spark duration significantly increases (as shown in Figure 29), hence discharges excessive spark energy while operating with 15% dilution.

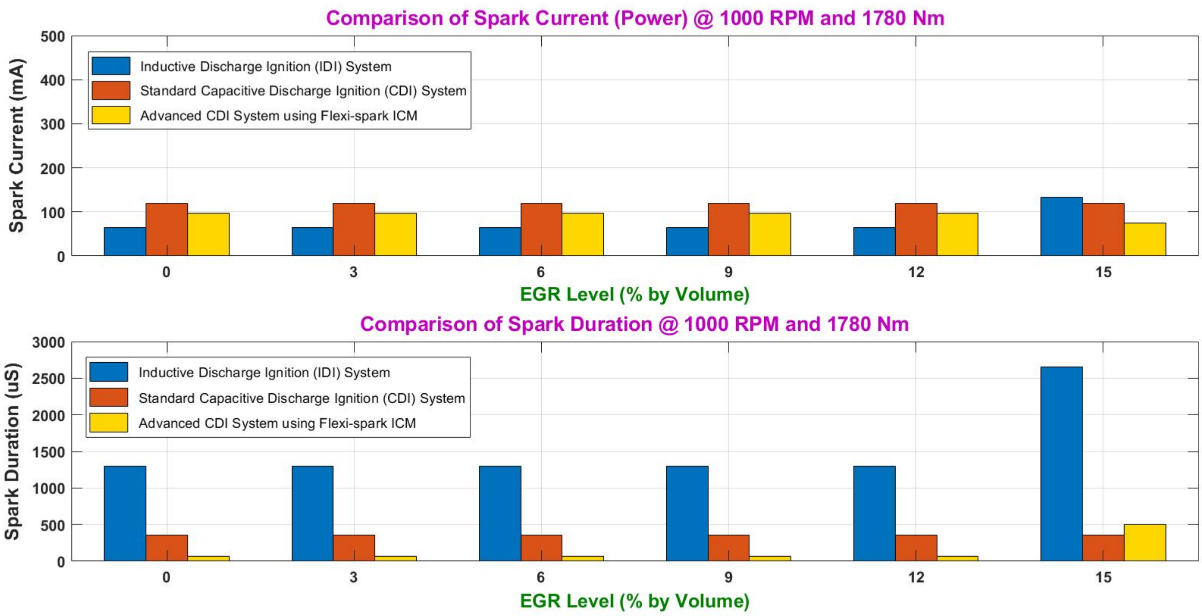


Figure 29: *Comparison of Other Spark Discharge Parameters @ 1000 RPM and 1780 Nm*

Finally, when the performances of an optimized ignition system 'FlexiSpark^{TM} CDI' is evaluated, it is found that at lower dilution levels, the energy discharged at the time of spark is much lower than the other tested ignition systems. With the availability of higher degrees of freedom to control the spark, it was made possible to trigger combustion by increasing the spark current (power). The temperature of charged gases being higher at the spark plug gap, made possible to hit the fuel-air mixture immediately within ~ 70µS of spark duration, even with 12% EGR content.

However, when running with 15% EGR, the duration of spark was enhanced to 500µS. The spark current, on the other hand, was kept at minimum as no improvement in combustion was noticed at high spark current (power) with standard CDI system. Therefore, by effectively varying the spark parameters, FlexiSpark^{TM} CDI system made possible to stably operate the engine with 15% EGR with minimal spark energy discharge from the coil.

Figure 30: *Comparison of Combustion Quality and Main Combustion Duration @ 1000 RPM and 1780 Nm*

Furthermore, total hydrocarbon emissions along with the combustion duration have been compared w.r.t EGR increment for the ignition systems (tested) to see if additional spark energy influences the main combustion process. After analysing both the parameters, as shown in Figure 30, it is comprehended that once a self-propagating flame has developed, the left-over spark energy is unwanted and therefore, leads to excess spark plug electrode wear.

4.6.2 Comparison at 1500 RPM – 1000 Nm

The performances of the ignition systems w.r.t EGR increment have been studied in this section, while running the engine at 1500 RPM with medium load condition.

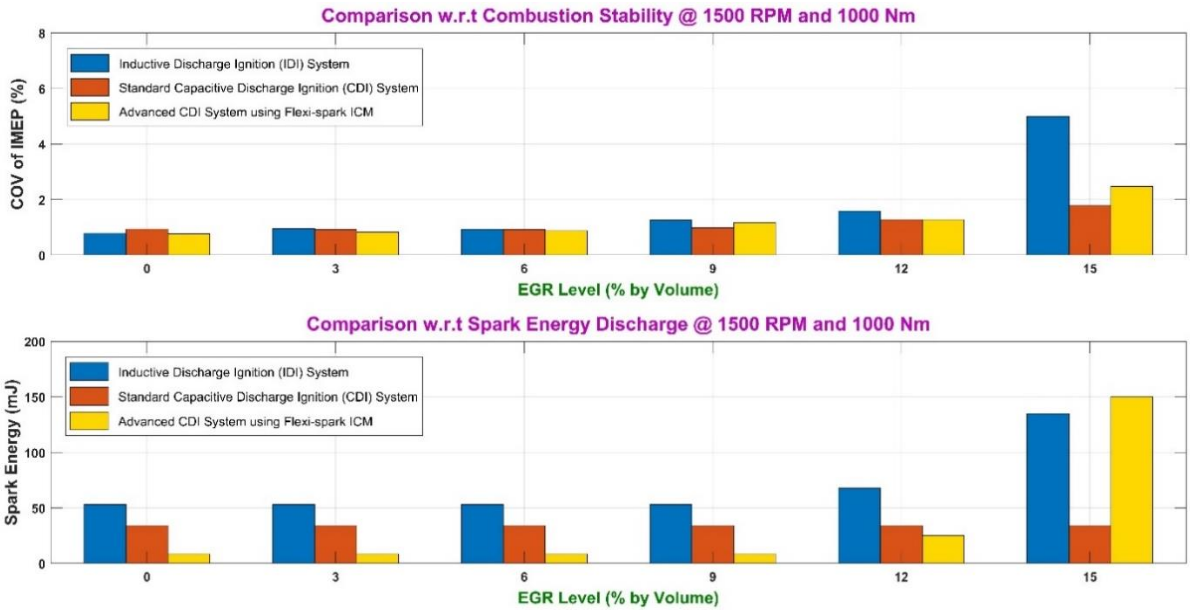


Figure 31: *Comparison of Combustion Stability vs Spark Energy Discharge @ 1500 RPM and 1000 Nm*

In the first place, it is found that the standard CDI system is able to ignite the fuel-air mixture with desired combustion stability ($COV_{IMEP} \leq 2.5\%$), even with 15% EGR (as shown in Figure 31). Being able to produce a high spark power (distributed over spark duration), it is comprehended that the standard CDI system was able to enhance the size of flame kernel large enough to develop a self-propagating flame nucleus within ~ 360µS. As an impact, the spark energy required to achieve a stable combustion reduced significantly, when running at 15% EGR.

On the other hand, the IDI system failed to provide the desired range of combustion stability at 15% EGR level, even with maximum spark energy discharge (~ 135 mJ) at the gap (as shown in Figure 31). Being a DC current, the availability of spark current/power (over spark duration) was lower due to its constant decaying nature over time. Hence, it is understood that the size of the flame kernel, being degraded over time, was not sufficient enough to develop a self-propagating nucleus of flame, even with ~ 2500µS of spark duration.

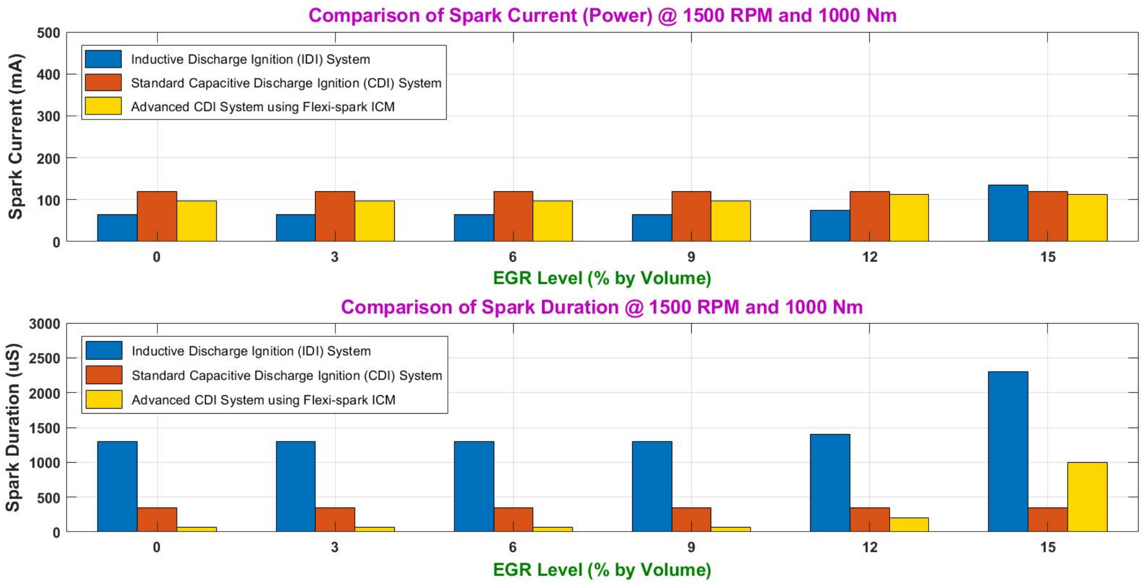


Figure 32: *Comparison of Other Spark Discharge Parameters @ 1500 RPM and 1000 Nm*

Finally, the FlexiSpark™ CDI system was able to trigger a self-sustaining combustion within ~ 70µS of spark duration (as shown in Figure 32), even with 9% EGR. Further addition of EGR (12%) was possible with the enhancement in spark current/power, distributed over spark duration (~ 70µS), hence keeping the spark energy discharge to its minimum, when compared to other ignition systems (tested).

However, when the engine was operated with 15% EGR, the stability of combustion was barely made possible after spark energy (~ 150mJ) was discharged at the spark plug gap. After studying other spark discharge parameters (as shown in Figure 32), it was the spark current (power) that influenced spark duration, hence spark energy. Therefore, it is comprehended that the spark power, being comparatively lower than standard CDI system, was not enough to develop a self-propagating flame-front due to high intensity of turbulences available near the spark plug gap. Hence, spark duration was needed to enhance ~ 1000µS (as shown in Figure 32) in-order to achieve a stable combustion, which in turn, enhanced excessive discharge of spark energy.

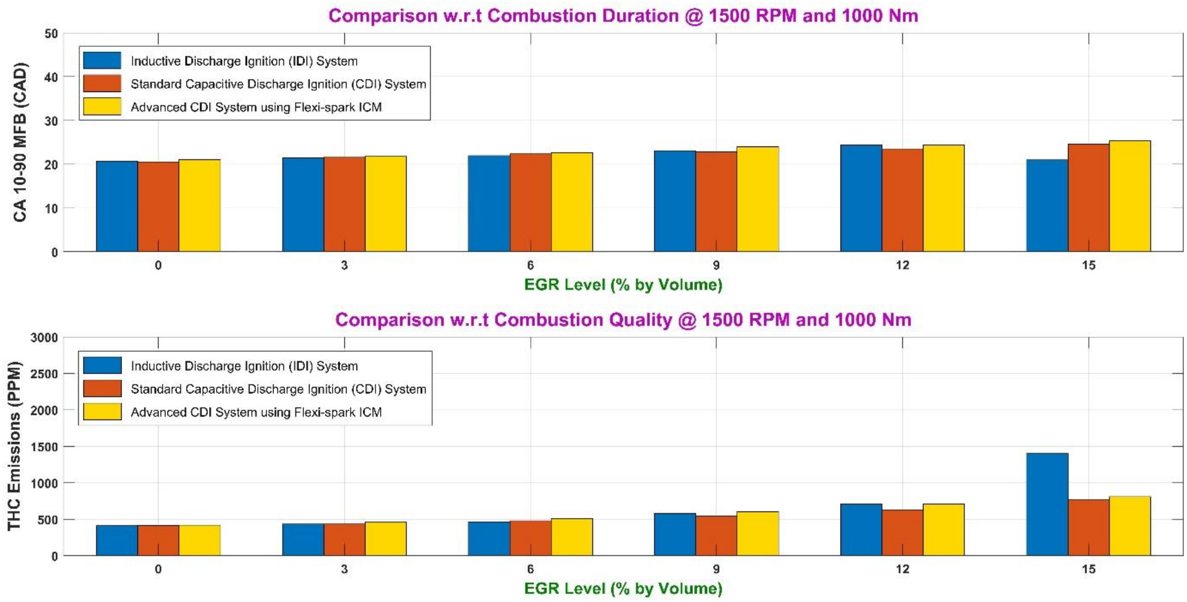


Figure 33: *Comparison of Combustion Quality and Main Combustion Duration @ 1500 RPM and 1000 Nm*

Other engine performance parameters were further reviewed (as shown in Figure 33) to see if there is any significant effect on combustion due to reduction in spark energy. Comparing the main combustion duration w.r.t the tested ignition systems, it is comprehended that once a stable flame-front has developed, it becomes independent of spark energy (if further added) and starts to propagate to the rest of the combustion chamber. A similar conclusion can also be drawn while comparing THC emissions since no significant improvement in combustion quality is found, even with excess spark energy discharge.

4.6.3 Comparison at 1000 RPM – 150 Nm

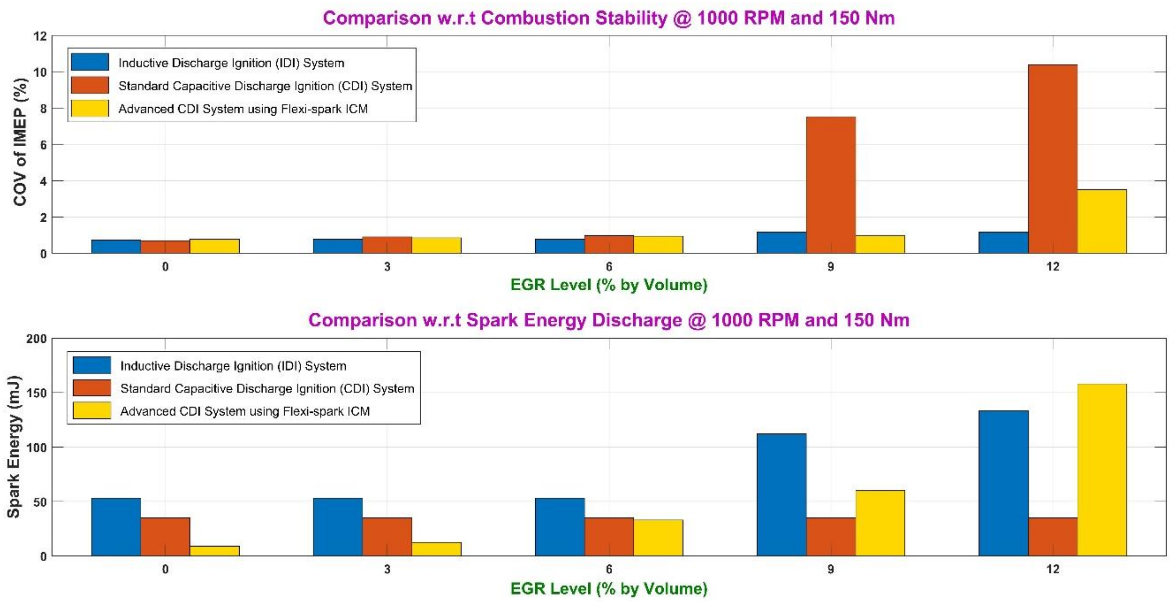


Figure 34: *Comparison of Combustion Stability vs Spark Energy Discharge @ 1000 RPM and 150 Nm*

In the first place, the performance of the standard CDI system is studied (as shown in Figure 34) and found that COV_{IMEP} was within the desired range (≤ 2.5%), even with 6% EGR. However, when the EGR level was increased to 9%, occasional misfires were noticed in multiple cylinders, giving a high rise to COV_{IMEP}. A proper justification can be made from spark duration (as shown in Figure 35), which is significantly shorter (~ 360µS). As an impact, the probability of hitting an appropriate fuel-air mixture to develop a stable flame nucleus reduced at high EGR level.

The IDI system on the other hand, managed to stably operate the engine with 12% EGR. However, the spark duration was significantly higher ~ 3800µS (as seen in Figure 35). As a result, spark energy discharge was way too high (~ 135 mJ), indicating a significant erosion of the sparkplug electrodes.

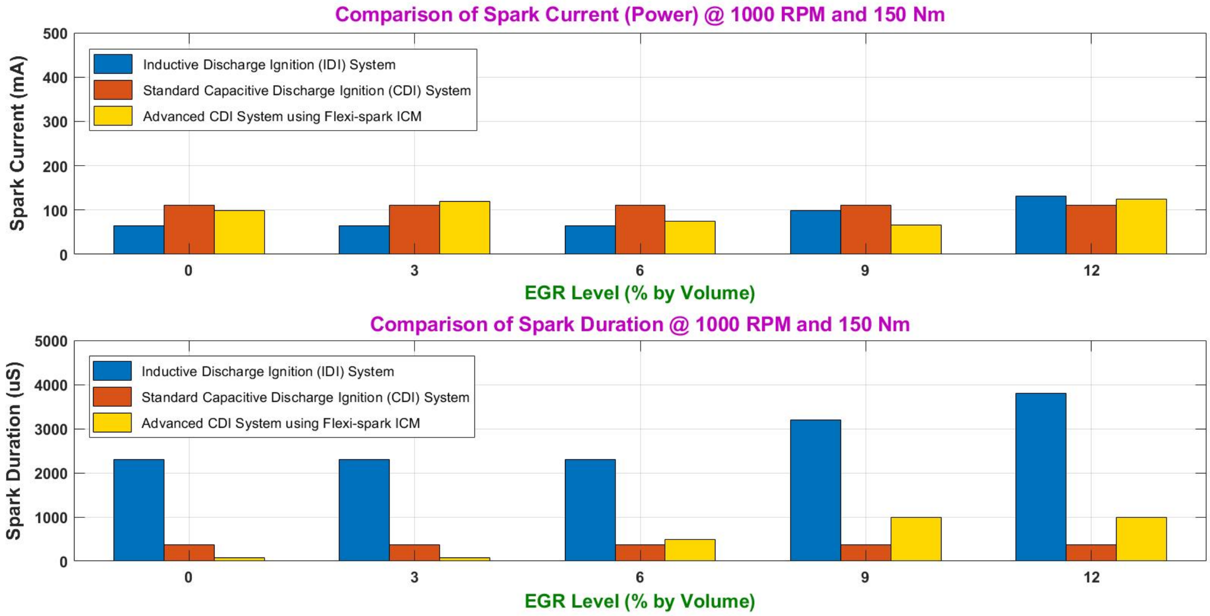


Figure 35: *Comparison of Other Spark Discharge Parameters @ 1000 RPM and 150 Nm*

Lastly, while reviewing the performance of FlexiSpark™ CDI system, a major reduction in spark duration was possible (as shown in Figure 35), even at 9% EGR. After closely reviewing other spark parameters, it is comprehended that spark current (power) being consistently distributed over the spark duration, the probability to develop a self-sustained flame-front increases. As an impact, a significant amount of spark energy can be saved from being wasted, by effectively varying spark duration.

However, when the EGR level was further enhanced to 12%, the combustion became unstable (COV_{IMEP} > 3%), due to lack of sufficient spark duration (as shown in Figure 35) to trigger a stable combustion.

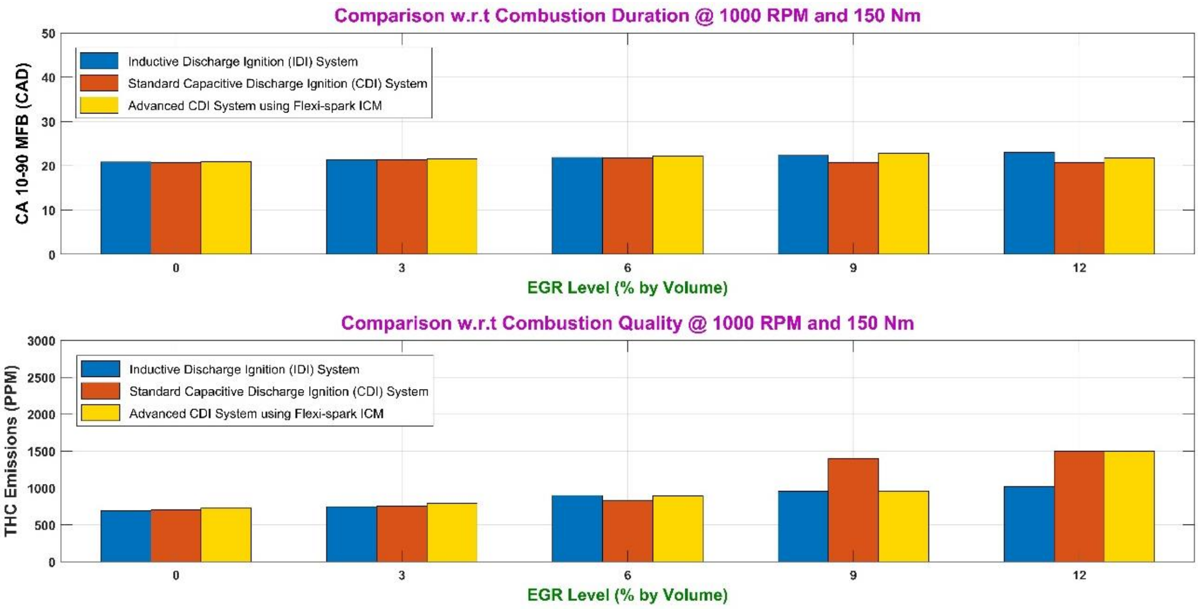


Figure 36: *Comparison of Combustion Quality and Main Combustion Duration @ 1000 RPM and 150 Nm*

A final review has been made by comparing both THC emissions and CA_{10-90} mass fraction burnt to see if excess spark energy reduces the total duration of combustion, hence improving combustion quality. After deeply analysing the comparison made in Figure 36, no significant improvement has been noticed in any of the ignition systems. Therefore, it is again comprehended that once the main combustion process is triggered, further addition of spark power and/or energy is not desirable.

5. Discussions

The ignition systems were tested at three different operating conditions. Here are some remarks obtained from analysis of the results, as discussed below:

a. Low Engine Speed (1000 RPM) – High Load (1780 Nm)

This engine must be operated at maximum possible dilution (EGR) level in-order to enhance the brake thermal efficiency and minimize the tendency of knocking, when running at higher loads. It is found that both IDI and FlexiSpark™ CDI system can be used to stably operate the engine under 15% diluted fuel-air mixtures. It is interesting to notice that only one-fifth of the duration (compared to an IDI system) is enough to achieve robust combustion using FlexiSpark™ CDI system while running the engine on same dilution level. Hence, an optimal spark design[10] for the tested ignition systems w.r.t amount of EGR (to be added) is proposed in Table 3.

Table 3: *Spark Design Strategy at 1000 RPM – 1780 Nm @ Available Spark Voltage < 20KV*

IGNITION SYSTEM	EGR (% by Vol.)	Spark Current (mA)	Spark Duration (μS)	Spark Energy (mJ)
Inductive (IDI)	12	65	1300	53
Standard CDI (Baseline)	12	119 (RMS)	360	34
FlexiSpark™ CDI	15	74 (RMS)	500	33

Therefore, a significant amount of spark energy can be scaled down when using an optimized ignition system, even with high addition of EGR.

b. High Engine Speed (1500 RPM) – Medium Load (1000 Nm)

At high engine speed, it is important to survive the turbulence intensity and hit the favourable fuel-air mixture to develop a self-propagating nucleus of flame. The standard CDI system succeeded in attaining upto 15% EGR with shorter spark duration due to high spark current (power), thereby overcoming turbulences with minimal spark energy discharge. On the other hand, due to internal limitations within FlexiSpark™ CDI system – Prototype 1, the spark power produced was comparatively lower than Standard CDI system. Therefore, spark duration was needed to enhance (~ 1000μS) in-order to achieve stable combustion, when running with 15% EGR. As a result, an excessive waste of spark energy is noticed, indicating a further upgradation is needed in FlexiSpark™ CDI system to minimize the electrodes wear. Considering all the facts, the best suitable spark design strategy[10] for this engine operating condition is recommended in Table 4.

[10] *The spark strategy for all the tested ignition systems has been designed by giving percentage of EGR as the highest weighing factor, followed by spark duration, spark energy and spark current.*

Table 4: Spark Design Strategy at 1500 RPM – 1000 Nm @ Available Spark Voltage < 20KV

IGNITION SYSTEM	EGR (% by Vol.)	Spark Current (mA)	Spark Duration (µS)	Spark Energy (mJ)
Inductive (IDI)	12	75	1400	68
Standard CDI (Baseline)	15	120 (RMS)	350	34
FlexiSpark™ CDI	12	113 (RMS)	200	25

c. Low Engine Speed (1000 RPM) – Low Load (150 Nm)

The pumping losses is one of the major issues with an SI engine while running at low load conditions. Therefore, it is desirable to robustly operate the engine with higher EGR level. It is noticed that IDI system has the ability to operate the engine with 12% EGR, at the cost of significantly high spark duration. However, a major reduction in spark energy discharge is still possible at 12% EGR by scaling down the spark current (power). The FlexiSpark™ CDI system on the other hand, can stably operate the engine with 9% EGR with only one-third of the spark duration (needed by an IDI system). Further addition of EGR was not possible due to internal limitations of the spark design parameters within FlexiSpark™ CDI system – Prototype 1. Hence, an optimal spark strategy[11] is outlined for the tested ignition systems at this operating point, as given in Table 5.

Table 5: Spark Design Strategy at 1000 RPM – 150 Nm @ Available Spark Voltage < 10KV

IGNITION SYSTEM	EGR (% by Vol.)	Spark Current (mA)	Spark Duration (µS)	Spark Energy (mJ)
Inductive (IDI)	9	98	3200	101
Standard CDI (Baseline)	6	110 (RMS)	370	34
FlexiSpark™ CDI	9	67 (RMS)	1000	60

[11] *The spark strategy for all the tested ignition systems has been designed by giving percentage of EGR as the highest weighing factor, followed by spark duration, spark energy and spark current.*

6. Conclusion and Future Recommendations

After comparing the performances of the tested ignition systems w.r.t multiple combustion parameters, the following conclusions can be drawn:

- ✓ Spark power is the best indicator of the Ignitability potential of an ignition system. It is the spark power that governs spark energy.
- ✓ Once a stable flame front is developed and starts to propagate, there is nothing more to gain by further increasing spark power and/or spark duration.
- ✓ Therefore, by effectively varying spark power (over time), the engine can still achieve a robust combustion with minimal spark duration.
- ✓ Thus, a major reduction in excessive discharge of spark energy is possible by using an optimized ignition system "FlexiSpark™ CDI", hence keeping the spark plug electrodes wear to a minimum. In short, *"Save Energy – Save Spark-plugs"*.

In future, further studies on Ignitability are recommended at other critical engine operating points. For instance, at high engine speed - high load condition, to identify the amount of EGR that can be added in-order to scale down exhaust gas temperature while assuring stable combustion (suggested by Volvo Penta).

Next to it, an in-depth analysis on spark plug electrodes wear mechanism is also proposed in-order to identify its dependence on both spark power and energy.

Lastly, it is also suggested to review if further spark energy can be reduced by increasing the volume of spark discharged over time, for instance, by increasing the spark plug electrodes gap.

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Appendix - I

Measurements in the Test Cell

EGR System

A long-route (low-pressure) EGR system was used i.e. exhaust gas was extracted downstream the exhaust turbine and further reintroduced upstream the compressor. In addition, an exhaust gas heat exchanger was also used to cool the EGR. A throttle (butterfly valve) was used on the inlet of the exhaust-gas side of the EGR cooler to control the amount of EGR to be delivered to the engine. The amount of EGR has been computed according to:

$$\% \text{ EGR} = \frac{CO2\ Inlet}{CO2\ Exhaust} * 100 \quad [\% \text{ by vol.}]$$

Cylinder Pressure

Every cylinder head was equipped with a piezo electric pressure transducer () in-order to trace in-cylinder pressures for heat release computations. The cylinder pressures were measured five times per crank angle degrees using an external crank angle encoder (1800 pulses per revolution).

Temperatures

The temperature at the exhaust manifold was measured using thermocouples. Alongside, temperature on the EGR system was measured after the EGR cooler to control the flow of water circulation through the heat exchanger in-order to maintain the EGR temperature. Furthermore, temperatures in the intake manifold (before and after the intercooler), cooling water, engine oil, etc. were also measured for supervision.

Emissions

Raw emissions were measured before the after-treatment system (by AVL AMA i60) to analyse the quality of combustion. The emissions system (used) consisted of a Flame Ionization Detector (FID) for hydrocarbons, a Chemiluminescence Detector (CLD) for nitric oxides and multiple Infra-red Detectors to measure carbon monoxide (CO) and carbon dioxide CO_2 (both in exhaust and intake manifold). The HC emissions have been presented as propane equivalent (C3) in the results (as discussed in the following chapter).

Ignition Parameters

The high voltage (≤ 50KV) in the secondary side of the ignition coil was measured by using a specialized capacitive probe (MI074 Secondary Ignition Pickup – by Pico Technology), as shown in figure. On the other hand, the spark current was computed by measuring the voltage across a resistor (10 ohm) in the return wire (from ignition coil to ICM) for both Standard CDI and Advanced CDI systems, using a DC voltage probe (RIGOL RP 2200) capable of measuring up to 300 volts.

However, when the Inductive Ignition (IDI) system was used for the experiment, the current was measured from the primary side of the coil (using a 30A - DC current clamp). Using the primary current, the secondary current and spark energy discharge were further computed from the datasheet provided by SEM AB[12].

Finally, all the measurements, taken from the ignition systems (tested) were recorded with a PC based oscilloscope (PicoScope 6000 Automotive) as shown in figure, using the sampling frequency at 80MS/sec.

(I-a) **(I-b)** **(I-c)**

Figure I-a: *MI074 Secondary Ignition Pickup*

Figure I-b: RP2200 DC Voltage Probe **Figure I-c:** PicoScope 6000 Series

Fuel – CNG Composition Data

Natural gas used in the experiment has its origin in the North Sea. The composition of the gas slightly varies over time as it is a mix from different locations of the sea. The lower heating value of the gas (used) was 47.68 MJ/kg.

Table 6: Fuel (CNG) Composition used in the Experiment

Substance	**% by Vol.**
CH_4 (Methane)	94.57
C_2H_6 (Ethane)	3.55
C_3H_8 (Propane)	0.67
C_4H_{10} and heavier	0.39
CO_2	0.5
N_2	0.3

[12] *Ignition coil 805 100 82 – Inductive Ignition Coil for CNG, LPG & Biogas fueled engines – SEM AB*

Appendix – II

FlexiSpark™ Modes – Combination of Spark Parameters

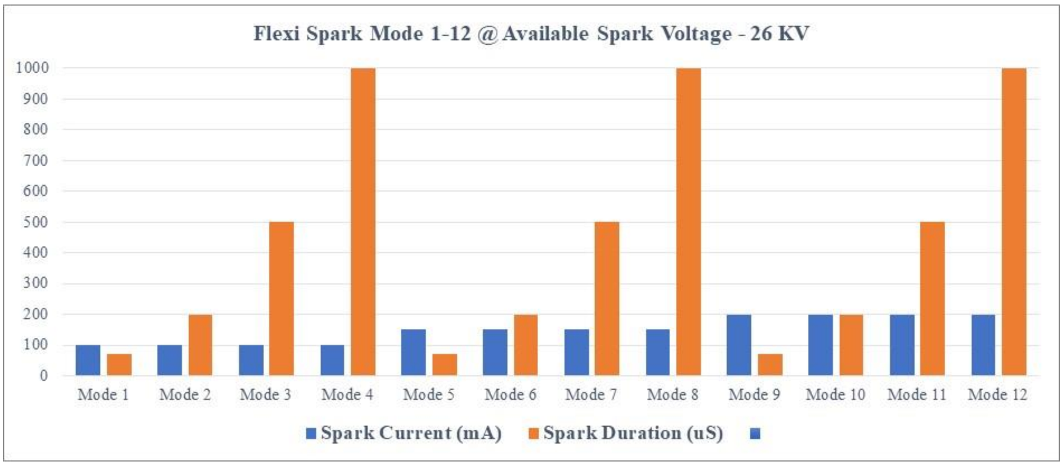

Figure A: *FlexiSpark™ – Spark Modes (1-12)*

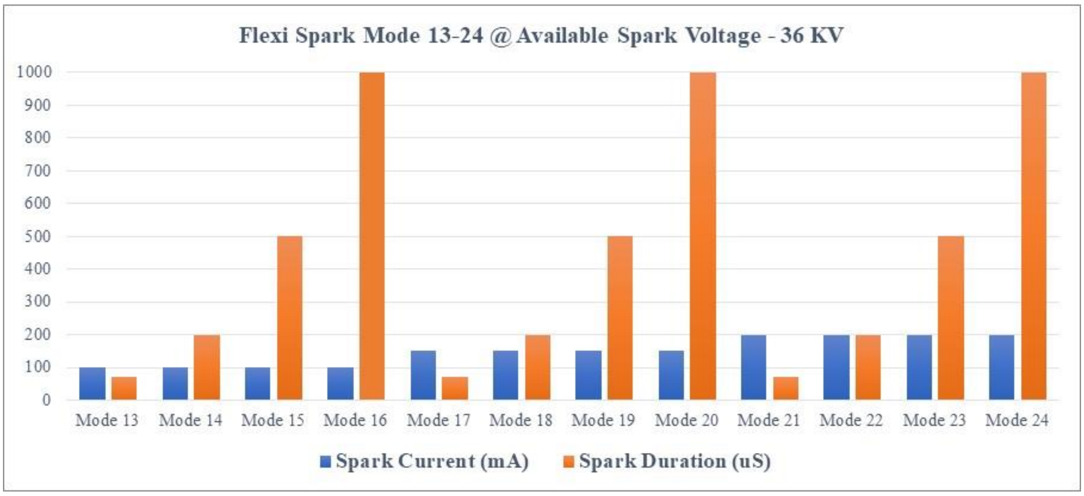

Figure B: *FlexiSpark™ – Spark Modes (13-24)*

FlexiSpark™ CDI System – Typical Spark Voltage and Current Waveforms

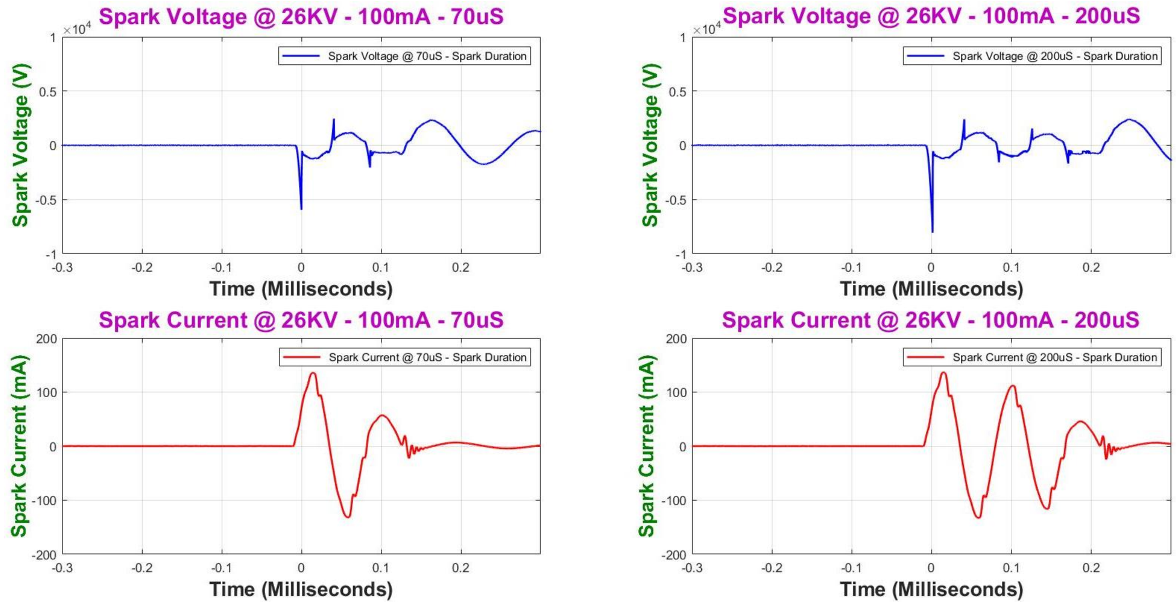

Figure C: *Typical Spark Voltage and Current Waveform @ 70µS and 200µS Spark Duration*

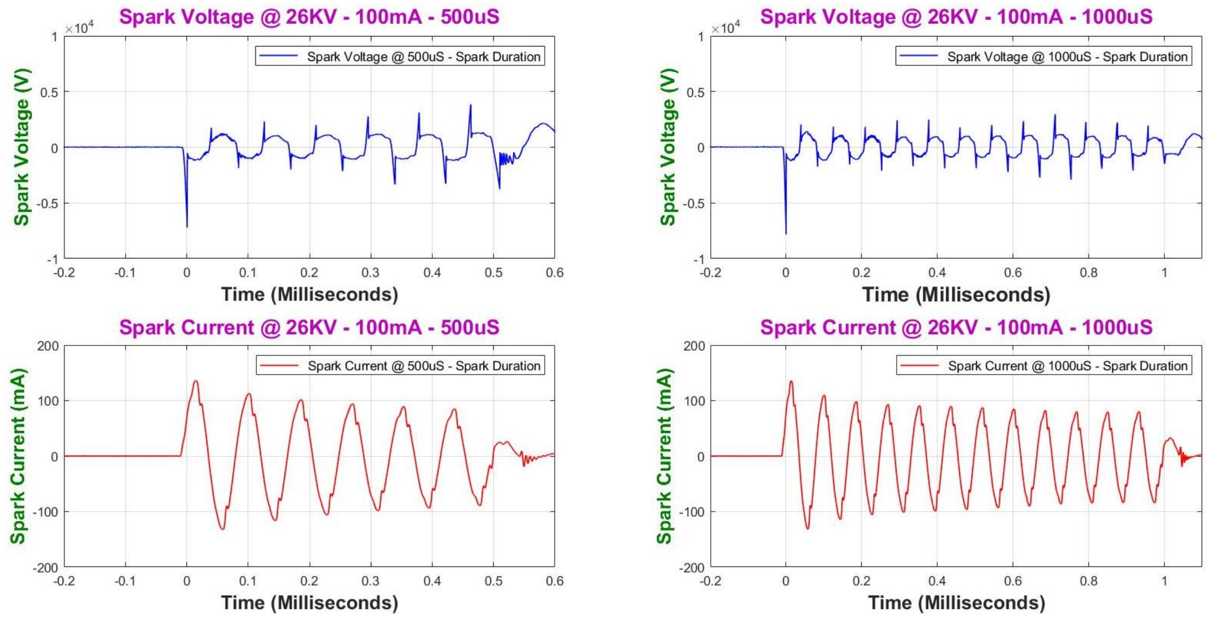

Figure D: *Typical Spark Voltage and Current Waveform @ 500µS and 1000µS Spark Duration*

Typical Spark Current and Voltage Waveforms (AC vs DC)

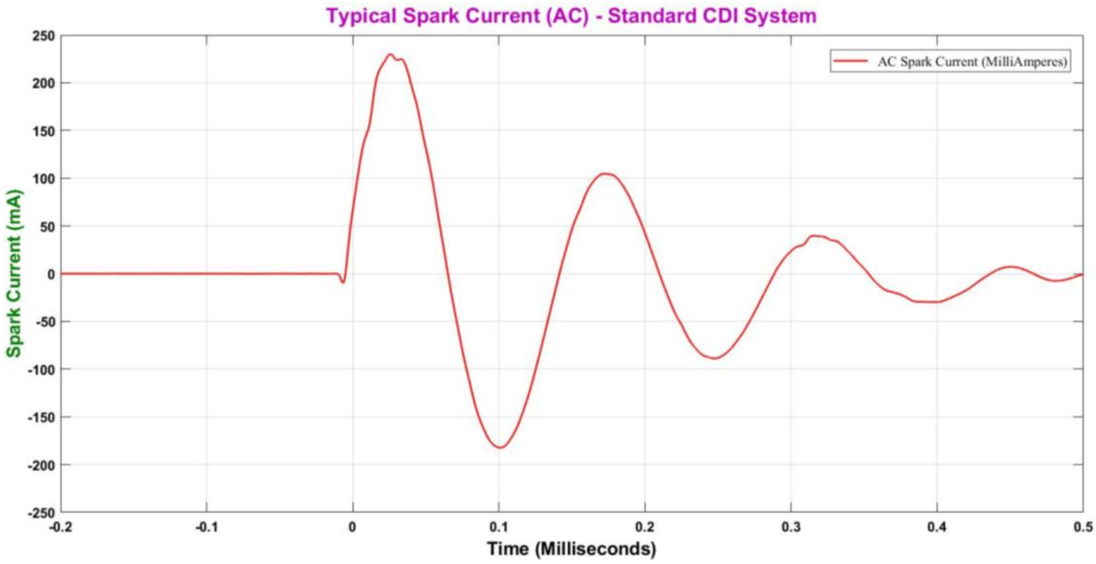

Figure E: *Typical AC Spark Current Waveform (Standard CDI System)*

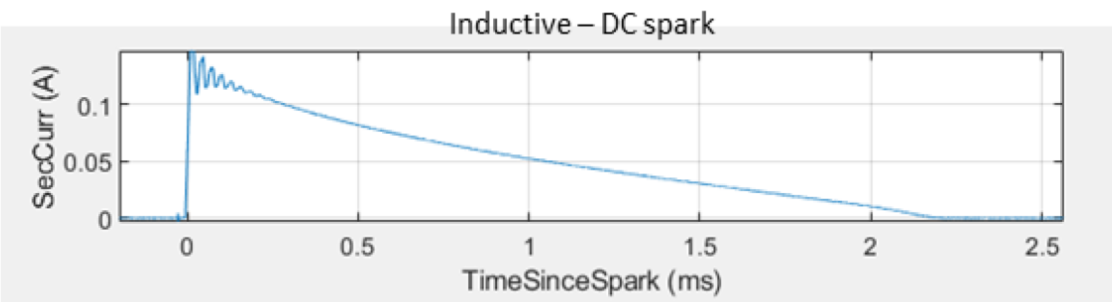

Figure F: *Typical DC Spark Current Waveform (Conventional IDI System) [17]*

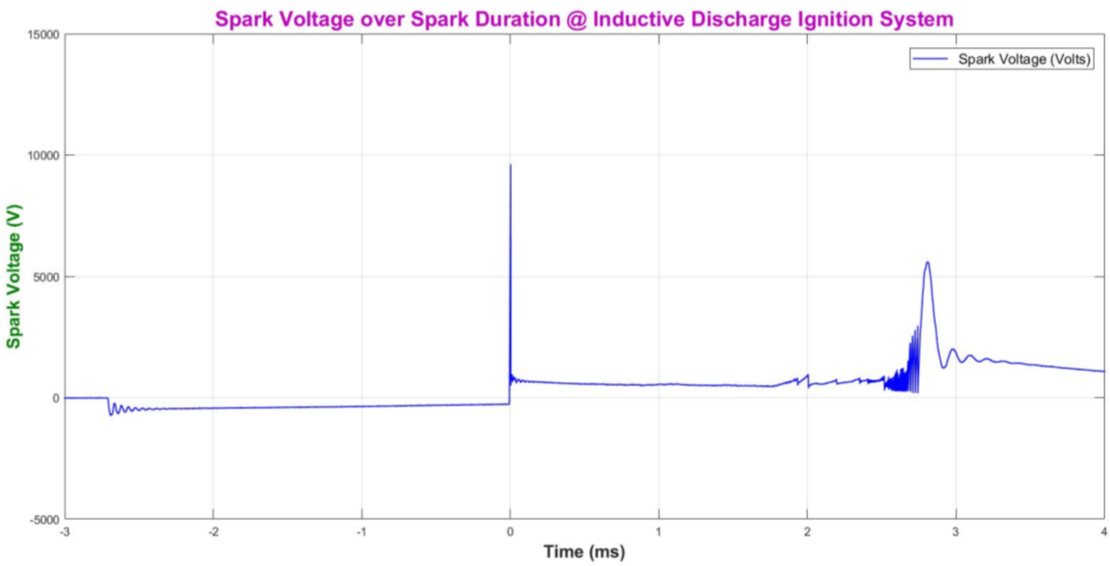

Figure G: *Typical DC Spark Voltage Waveform (Conventional IDI System)*