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The Effect of Spark Plug Types on Engine Performance and Emissions

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Abstract

There are many different spark plug designs available in the market nowadays. Understanding the differences between them is beneficial in helping the engine to run properly and efficiently. In the present study, a group of spark plugs with different characteristics by electrode gap, number of electrode, projection in cylinder and geometry of electrodes were chosen to explore their impact on the engine performance and emissions. In an attempt to enhance engine performance, smoothness and reducing fuel consumption and emissions.

Keywords: spark plug,internal combustion engine, electrodes, emissions, fuel.

العديد من أنواع شمعات الاشتعال تنتج هذه الأيام، فهم هذه الأنواع والفرق بينها يساعد على تشغيل المحركات بشكل أفضل ورفع كفاءتها. في هذه الدراسة سيتم تجريب مجموعة من شمعات الاشتعال المختلفة من حيث عدد الأقطاب و شكلها، و المسافة بين القطب الموجب والسالب، و امتداد شمعات الاشتعال إلى داخل المحرك، بهدف معرفة اثر هذه الاختلافات على اداء المحرك وعملية الاحتراق وغازات العادم الصادرة من المحرك، في محاولة لتحسين أداء محركات الاحتراق الداخلي و تقليل استهلاكها للوقود وتقليل كمية غازات العادم.

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Chapter 1

Introduction

1.1 Project Overview

Internal combustion engine is an engine in which the combustion takes place internally. Combustion of a fuel occurs with an oxidizer, usually air in a combustion chamber. The combustion process in spark ignition engines plays a key role in the conversion of fuel energy into mechanical energy.

The gasoline or spark-ignition (SI) internal combustion engine uses the Otto cycle and externally supplied ignition. It burns an air/fuel mixture and in the process converts the chemical energy in the fuel into kinetic energy. After ignition at the spark plug, the mixture of fuel and air starts to burn and continues burning until consuming the whole of the fuel of the charge in the cylinder. After the combustion process ends, exhaust gases are rejected from the engine to the surrounding atmosphere. The major exhaust emissions are Unburned Hydrocarbons (HC), Nitrogen Oxides (NO_x) and Carbon Monoxide (CO).

Today, there is a wide variety of spark plug designs available in the market. Understanding the differences between them is beneficial in helping the engine to run properly and efficiently. Major types of spark plug designs in production include standard J-gap, fine center and/or ground electrodes, surface gap, multiple ground electrodes, and their combinations.

The design of spark plug center and ground electrodes is an important factor which plays a key role in the effectiveness of spark plugs. Over the past few decades, a number of studies have been conducted to understand the effects of spark plug design on spark-ignition engine performance in various aspects. Number of electrodes, shape, size, material, gap projection, and orientation are the main parameters under investigations. Higher ignitability with more sustainability spark plugs were the main targets for these studies especially in case of lean mixtures.

In a conventional spark plug, the discharge energy is normally deposited at one fixed point, or over a relatively large area while in modified spark plugs where multiple electrodes are used, the possibility of getting a rotating spark over different electrodes and points helps in improving the spark plug durability and extend lean stability limits beside the probability of getting better burning rate.

On the other hand, it was believed that less amount of material near the gap is a major contributing factor for more rapid growth of the flame kernels. This means that larger electrodes increase the heat loss from the initial flame kernel while the rate of initial flame kernel development is adversely affected.

In this study several spark plugs will be compared with respect to their effect on engine performance, stability, fuel consumption and emissions. The main factors considered to affect number of electrodes.

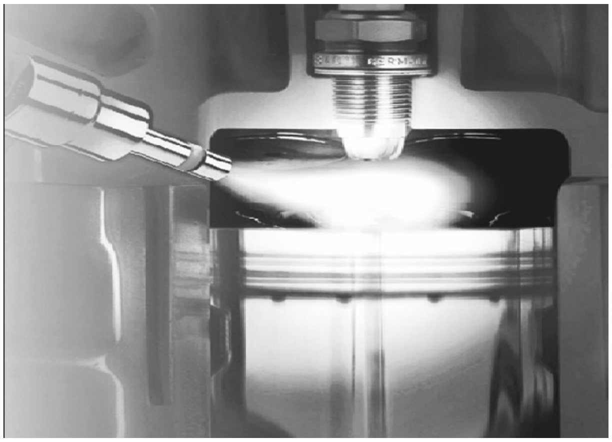


Figure 1.1: Spark Plug in Gasoline Engine

1.2 Project Objective

The objective of this project is a comparison between type spark plugs with respect to combustion performance and emission. considering the spark plug number of electrode effect on combustion and emission .

1.3 Project Choice and Justification

Contributing to the improvement of internal combustion engines and reducing the fuel consumption and emissions.Studying the effect of spark plug on engine noise in order to improve its smoothness.

1.4 Time Table

In this section the tasks and time tables will be determined as shown below:

Table 1.1: Tasks description

Task ID	**Task Description**
	1^{st} semester
T1	Project selection
T2	Collection reference from library
T3	Collection reference from website
T4	Selecting the project scope and the operation model
T5	Selecting the major parameter
T6	Study and analysis of information on the project
T7	The collection of information that have been studied
T8	Write the project and preparing the 1^{st} semester presentation
	2^{nd} semester
T9	Editing the introduction of the project
T10	check the missed and damaged parts of the test unit
T11	Finding, buying and preparing the replacement parts
T12	Preparing the test unit for operation and replacing the missed and damaged parts
T13	Calibrating the equipments and testing it
T14	Performing the experiment and collecting data
T15	Analyzing the collected data
T16	Write the project and preparing the 2^{nd} semester presentation

Table 1.2: Time table

1st semester															
Task/Week	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
T1	■	■													
T2			■	■											
T3					■	■									
T4						■	■	■							
T5								■	■						
T6									■	■	■				
T7											■	■			
T8							■	■	■	■	■	■	■	■	■
2nd semester															
T9	■	■													
T10			■	■											
T11					■	■									
T12						■	■	■							
T13								■	■						
T14									■	■	■				
T15											■	■			
T16												■	■	■	

Chapter 2

Spark Plug

The air/fuel mixture in the gasoline or spark-ignition engine is ignited electrically. Electrical energy drawn from the battery is temporarily stored in the ignition coil for this purpose. The high voltage generated within the coil produces a flashover between the spark-plug electrodes in the engine's combustion chamber. The energy contained in the spark then ignites the compressed air/fuel mixture.

2.1 Function

The function of the spark plug is to introduce the ignition energy into the gasoline engine's combustion chamber and to produce a spark between the electrodes to initiate combustion of the air/fuel mixture. Spark plugs must be designed to ensure positive insulation between spark and cylinder head while also sealing the combustion chamber. In combination with engine components, such as the ignition and mixture-formation systems, the spark plug plays a crucial role in determining operation of the gasoline engine. It must facilitate reliable cold starts, ensure consistent operation with no ignition miss throughout its service life, and not overheat under extended operation at or near top speed. To ensure this kind of performance throughout the spark plug's service life, the correct plug concept must be established early in the engine-design process. Research investigating the ignition process is employed to determine the spark-plug concept that will produce the best emissions and most consistent engine operation. An important spark-plug parameter is the heat range. The right heat range prevents the spark plug from overheating and inducing the thermal auto ignition that could lead to engine damage[5].

2.2 Parts

The essential components of the spark plug are see in figure (2.1).

1. Terminal stud.
2. Insulator.
3. Shell.
4. Seal seat
5. Electrodes

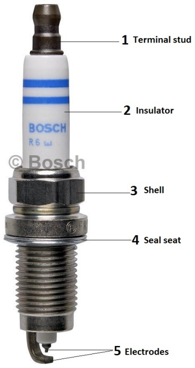


Figure 2.1: Spark Plug Parts

2.2.1 Terminal Stud

The steel terminal stud is mounted gas-tight in the insulator with an electrically conductive glass seal, which also establishes the connection to the center electrode. The terminal end protruding from the insulator features a thread for connecting the spark-plug connector of the ignition cable. Terminal nut (with the required outer contour) is screwed onto the terminal-stud thread, or the stud is equipped with a solid connection manufacture.

2.2.2 Insulator

The insulator is cast in a special ceramic material. Its function is to insulate the center electrode and terminal stud from the shell. The demand for a combination of good thermal conductivity and effective electrical insulation is in contrast to the properties displayed by most insulating substances. Bosch uses Aluminum oxide (Al_2O_3) along with small quantities of other substances . Following firing, this special ceramic meets all requirements for mechanical and chemical durability, while its dense microstructure provides high resistance to disruptive discharge. On air-gap spark plugs, the outer contour of the insulator nose can also be modified to improve heating for better response during repeated cold starts [5].

2.2.3 Shell

The shell is manufactured from steel in a cold-forming process. The shell castings emerge from the pressing tool with their final contours, limiting subsequent machining operations to just a few areas.

The bottom end of the shell includes threads, making it possible to install the plug in the cylinder head and then remove it after a specified replacement interval. Depending on the specific design, as many as four ground electrodes can be welded to the end of the shell. An electroplated nickel coating is applied to the surface to protect the shell against corrosion and prevent it from seizing in the sockets of the Aluminum cylinder heads. To accommodate the spark plug-wrench, the upper section of the conventional shell has a 6-point socket fitting; newer shell designs may use a 12-point fitting. The 12-point fitting makes it possible to reduce the socket attachment's size to 14 mm without modifying insulator-head geometry. This reduces the spark plugs space demands in the cylinder head and allows the engine designer greater freedom in locating the cooling passages. The top end of the spark-plug shell is flanged after the plug core (comprising insulator with reliably mounted center electrode and terminal stud) has been inserted, and secures the plug core in position. The subsequent shrink-fitting process inductive heating under high pressure produces a gas tight connection between insulator and shell to ensure effective thermal conductivity

2.2.4 Seal Seat

Depending on engine design, either a flat or conical seal seat effects the seal between the spark plug and the cylinder head. In the case of a flat seal seat, a sealing ring is used as the sealing element. This captive sealing ring is permanently attached to the spark-plug shell. Its special contours adapt to form a durable yet flexible seal when the spark plug is installed. In the case of a conical seal seat, a conical, or tapered, surface on the spark-plug shell mates directly with the cylinder head to provide a seal without the use of a sealing ring [5].

2.2.5 Electrodes

During flashover and high-temperature operation, the electrode material is subjected to such strong thermal load that the electrodes become corroded and the electrode gap widens accordingly. To satisfy demands for extended replacement intervals, electrode materials must effectively resist erosion (burning by the spark) and corrosion (wear due to aggressive thermo chemical processes). These properties are achieved primarily through the use of temperature-resistant Nickel alloys. Electrodes are divided to ground and center electrode, and here is a description of them.

- Center electrode

The center electrode (Figure. 2.1a), which includes a Copper core for improved heat dissipation, is anchored at one end in the conductive glass seal. In “long-life” spark plugs, the center electrode serves as the base material for a noble-metal pin, which is permanently connected to the base electrode by means of laser welding. Other spark plug designs rely on electrodes formed from a single thin Platinum wire, which is then sintered to the Ceramic base for good thermal conductivity.

- Ground electrodes

The ground electrodes (Figure. 2.1b) are attached to the shell and usually have quadrilateral cross-sections. Available arrangements include the front electrode and the side electrode (Figure. 2.1). The ground electrode’s fatigue strength is determined by its thermal conductivity. As with center electrodes, composite materials can be used to improve heat dissipation, but it is the length and the end surface that will ultimately determine the ground electrode’s temperature, and thus its resistance to wear.

2.3 Spark Plug Concepts

The mutual arrangement of the electrodes and the locations of the ground electrodes relative to the insulator determine the type of spark-plug concept (Figure. 2.2). Air-gap concept, center and ground electrodes are configured to produce a linear spark to ignite the air/fuel mixture located within the space between them [5].

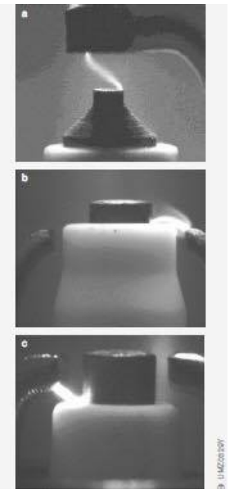


Figure 2.2: Spark-plug concepts

Surface-gap concept, as a result of the defined position of the ground electrodes relative to the Ceramic, the spark travels initially from the center electrode across the surface of the insulator nose before jumping across a gas-filled gap to the ground electrode. Because the ignition voltage required to produce discharge across the surface is less than that needed to produce discharge across an air gap of equal dimensions, a surface-gap spark can bridge wider electrode gaps than an air-gap spark with an identical ignition-voltage demand. This produces a larger flame core for more effective creation of a stable flame front. The surface-gap spark also promotes self cleaning during repeated cold starts, preventing soot deposits from forming on the insulator nose. This improves performance on engines exposed to frequent cold starts at low temperatures.

Surface-air-gap concepts, the ground electrode is arranged at a specific distance from the center electrode and the end of the Ceramic insulator. This produces two alternate spark paths, which facilitate both forms of discharge (air gap and surface-air gap) and different ignition-voltage-demand values. Depending on operating conditions and spark-plug condition (wear), the spark travels as an air-gap or surface-air-gap spark.

2.4 Electrode Gap

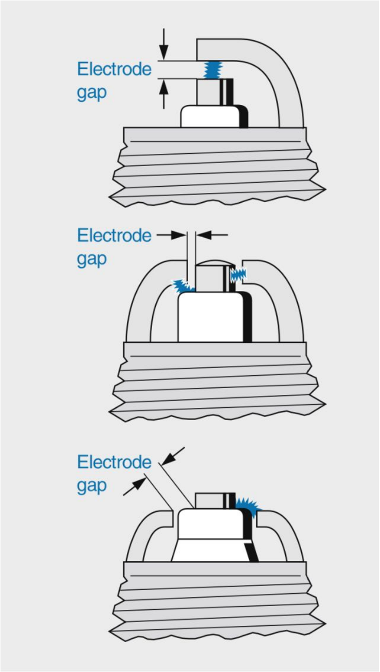


Figure 2.3: Electrode gap

As the shortest distance between the center and ground electrodes, the electrode gap determines the length of the spark (Figure. 2.3). The smaller the electrode gap, the lower the voltage that is required to generate an ignition spark.

An excessively small gap produces only a small flame core in the electrode area. Because this flame core loses energy through the electrode contact surfaces (quenching), the rate at which the flame core propagates is only very slow. Under extreme conditions, the energy loss can be high enough to produce ignition miss.

As electrode gaps increase, lower quenching losses lead to improved conditions for ignition, but larger gaps also increase the ignition-voltage demand. The reserves afforded by any given level of ignition voltage in the ignition coil are reduced and the danger of ignition miss increases [5].

2.5 Spark plug Performance

Because spark plugs operate within an aggressive atmosphere, sometimes at extremely high temperatures, electrodes are subject to wear, which increases the ignition-voltage demand. When the situation finally reaches the point at which the ignition-voltage demand can no longer be covered by the ignition coil, then ignition misses occur.

Spark-plug operation can also be detrimentally affected by changes in an aging engine and by contamination. As engines age, blow by and leakage increase, raising the amount of oil in the combustion chamber. This, in turn, leads to more deposits of soot, ash and Carbon on the spark plug, which can give rise to shunting, ignition misses, and in extreme cases auto-ignition. Yet another factor is the use of antiknock additives in fuels which can form deposits, become conductive at high temperatures, and produce hot shunts. The ultimate result is ignition miss, characterized by a substantial increase in pollutant emissions along with potential damage to the catalytic converter. This is why spark plugs should be replaced at regular intervals [5].

2.6 Electrode Wear

Flashover of electrical sparks causes the electrodes to heat up to their melting point. The vary small, microscopic particles deposited on surfaces react with the Oxygen or the other constituents of the combustion gases. This results in material erosion, widening the electrode gap and raising the ignition-voltage demand.

Electrode wear is minimized by using materials with high temperature stability (e.g., Platinum and Platinum alloys). It is also possible to reduce erosion without limiting service life using suitable electrode geometry (e.g., smaller diameter, thin pins) and alternate spark-plug designs (surface-gap plugs).

2.7 Abnormal Operating States

Abnormal operating states can destroy both the spark plugs and the engine. Such states include: Auto-ignition Combustion knock, and High oil consumption (ash and Carbon deposits) Engine and spark plugs can also be damaged by incorrect ignition-system settings, spark plugs with the wrong heat range for the engine, and unsuitable fuels.

2.8 Auto Ignition

Auto-ignition is an uncontrolled ignition process accompanied by increases in combustion chamber temperatures severe enough to cause serious damage to both spark plugs and engine. Full-load operation can produce localized hot spots and induce auto-ignition in the following areas: At the spark-plug's insulator nose on exhaust valves On protruding sections of cylinder head gaskets, and on flaking deposits.

2.9 Combustion Knock

Knocking is characteristic of an uncontrolled combustion process with very sharp rises in pressure. Knock is caused by spontaneous ignition of the mixture in areas which the advancing flame front, initiated by the usual electrical spark, has not yet reached. Combustion proceeds at a considerably faster rate than normal. High-frequency pressure pulsations with extreme pressure peaks are then superimposed on the normal pressurization curve(Figure 2.5) . The severe pressure gradients expose components (cylinder head, valves, pistons and spark plugs) to extreme thermal loads capable of damaging one or numerous components. On the spark plug, pitting on the ground electrode's surface is the first sign of combustion knock [5].

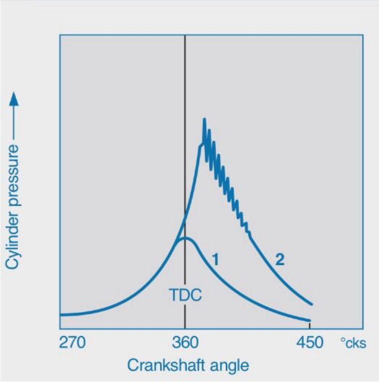


Figure 2.4: 1 Normal combustion, 2 Combustion knock.

Chapter 3

Combustion and Emission

3.1 Ignition System

The gasoline, or spark-ignition, engine is an internal combustion machine that relies on an external source of ignition-energy to run. An ignition spark ignites the air/fuel mixture compressed in the combustion chamber to initiate the combustion process. This ignition spark is generated by a flashover between the electrodes of a spark plug extending into the combustion chamber. The ignition system must generate adequate levels of high voltage energy to generate the flashover at the spark plug while also ensuring that the ignition spark is triggered at precisely the right instant [5].

A magnetic field is built up in the ignition coil when a current flows in the primary circuit. The ignition energy required for ignition is stored in this magnetic field. Interrupting the coil current at the moment of ignition causes the magnetic field to collapse. This rapid magnetic field change induces a high voltage on the secondary side of the ignition coil as a result of the large number of turns (turns ratio approx. 1:100). When the ignition voltage is reached, flashover occurs at the spark plug and the compressed air/fuel mixture is ignited.

The current in the primary winding only gradually attains its setpoint value because of the induced countervoltage. Because the energy stored in the ignition coil is dependent on the current, a certain amount of time (dwell period time) is required in order to store the energy necessary for ignition. This dwell period is dependent on, among others, the vehicle system voltage. The ECU program calculates from the dwell period and the moment of ignition the cut in point, and cuts the ignition coil the ignition driver stage and out again at the moment of ignition [5].

After the flashover, the voltage at the spark plug drops to the spark voltage, the spark voltage is dependent on the length of the spark plasma (electrode gap and deflection due to flow) and ranges between a few hundred volts and well over 1 kV. The ignition coil energy is converted in the ignition spark during the ignition spark period; this spark duration lasts between 100 μ over 2 ms. Following the breakaway of the spark, the attenuated voltage decays. The electrical spark between the spark plug electrodes generates a high-temperature plasma. When the mixture at the spark plug is ignitable and sufficient energy is supplied by the ignition system, the flame core that is created develops into an automatically propagating flame front. The following figure(3.1) represent the basic parts of ignition system.

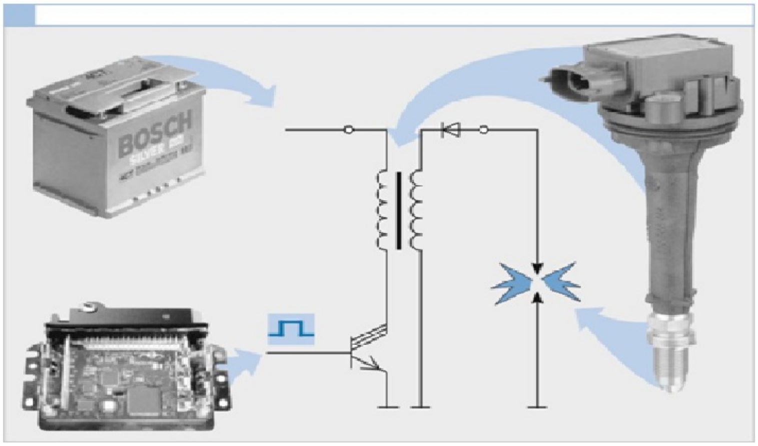


Figure 3.1: Ignition System

3.2 Combustion and Flame

The combustion is defined as a rapid chemical reaction between the Hydrogen and Carbon with Oxygen in the air and liberates energy in the form of heat.

3.2.1 Combustion stages

The pressure variation due to combustion in a practical engine is see in figure (3.2). In this figure, A is the point of passage of spark (say 20° bTDC), B is the point at which the beginning of pressure rise can be detected (say 8° bTDC) and C the attainment of peak pressure. Thus AB represents the first stage, BC the second stage and CD the third stage [6].

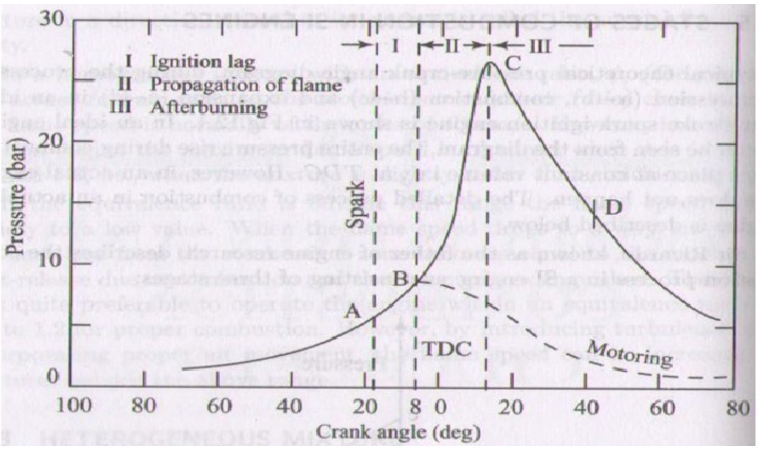


Figure 3.2: Stages of Combustion in an SI Engines

1. Ignition lag stage

   There is a certain time interval between the instant of spark and the instant where there is a noticeable rise in pressure due to combustion, this time lag is called ignition lag. Ignition lag is the time interval in the process of chemical reaction during which molecules get heated up to self ignition temperature, get ignited and produce a self propagating nucleus of flame. This chemical process depends upon the nature of fuel, temperature and pressure, proportions of exhaust gas residual and rate of oxidation or burning.

2. Flame Propagation Stage

   The second stage is a physical one and it is concerned with spread of the flame throughout the combustion chamber. The starting point of the second stage is where the first measurable rise of pressure is seen on the indicator diagram, This can be seen from the deviation from the motoring curve. During the second stage the flame propagates practically at a constant velocity. Heat transfer to the cylinder wall is low, because only a small part of the burning mixture comes in contact with the cylinder wall during this period. The rate of heat-release depends largely on the turbulence intensity and also on the reaction rate which is dependent on the mixture composition. The rate of pressure rise is proportional to the rate of heat release because during this stage, the combustion chamber volume remains practically constant (since piston is near the top dead center)[6].

3. After Burning Stage

   The starting point of the third stage is usually taken as the instant at which the maximum pressure is reached on the indicator diagram. The flame velocity decreases during this stage. The rate of combustion becomes low due to lower flame velocity and reduced flame front surface. Since the expansion stroke starts before this stage of combustion, with the piston moving away from the top dead center, there can be no pressure rise during this stage.

3.3 Factors Influencing the Flame Speed

The study of factors which affect the velocity of flame propagation is important since the flame velocity influences the rate of pressure rise in the cylinder and it is related to certain types of abnormal combustion that occur in spark-ignition engines.

3.3.1 Turbulence

The flame speed is quite low in non-turbulent mixtures and increases with increasing turbulence. This is mainly due to the additional physical intermingling of the burning and unburned particles at the flame front which expedites reaction by increasing the rate of contact. The increase of flame speed due to turbulence reduces the combustion duration and hence minimizes the tendency of abnormal combustion. However, excessive turbulence may extinguish the flame resulting in rough and noisy operation of the engine[6].

3.3.2 Fuel-Air Ratio

The fuel-air ratio has a very significant influence on the flame speed. The highest flame velocities (minimum time for complete combustion) are obtained with somewhat richer mixture which shows the effect of mixture strength on the rate of burning as indicated by the time taken for complete burning in a given engine. When the mixture is made leaner or richer the flame speed decreases. Less thermal energy is released in the case of lean mixtures resulting in lower flame temperature. Very rich mixtures lead to incomplete combustion which results again in the release of less thermal energy.

3.3.3 Engine Size

The size of the engine does not have much effect on the rate of flame propagation. In large engines the time required for complete combustion is more because the flame has to travel a longer distance. This requires increased crank angle duration during the combustion. This is one of the reasons why large sized engines are designed to operate at low speeds.

3.4 Effect of spark Plug on Combustion

There are many parameters related to spark plug that affect the combustion process. Among them, the electrode gap, spark plug projection, and number of electrode will be studied.

3.4.1 Number of Electrodes

Increasing the number of electrodes will increase the contact area between the flame kernel and the electrodes, it will also increase the mass of metal near the flame kernel. Both of those points increase the energy loss from spark and flame kernel to the spark plug which reduces its ability to grow and propagate through the combustion chamber. Hence negatively affecting the engine stability and increasing the probability of misfire especially at high engine speeds and lean mixtures [4] .

3.4.2 Spark Plug Gap

Spark plug gap is another factor influencing the mixture ignitability. Larger gaps increase the voltage requirements and the energy release rate becomes faster and the spark duration becomes smaller . The formation of flame kernel is slow in very small gaps due to the strong quenching effect of the electrodes. Heat loss by the ground electrode is increased significantly when the spark gap is narrowed (from 1.1 to 0.6 mm).

3.4.3 Projection of Spark Plug

As the volume and velocity of air/fuel rushing into the cylinder increases, greater spark plug tip projection increases the probability of spark blow out. Because of this, spark plugs rated for higher output engines are designed to have less projection into the cylinder. This minimizes the spark kernel's being exposed to the incoming fuel charge, and helps to eliminate spark blowout while increasing performance and reliability of the ignition system.

The reverse holds true for lower power engines. As power levels decrease so does the volume and velocity of the fuel charge. In order to reliably ignite these lower volumes of air and fuel it is better to project the spark plug as deeply as possible into the combustion chamber, moving the kernel directly into the air/fuel path [1] .

3.5 Emissions

3.5.1 Introduction

Internal combustion engines generate undesirable emissions in the combustion process. These emissions pollute the environment and contribute to global warming, acid rain, smog, odors, and respiratory and other health problems.

Engine emissions can be classified into two categories. Firstly, exhaust emissions, the major causes of these emissions are non stoichiometric combustion, dissociation of Nitrogen, and impurities in the fuel and air. The emissions of Concern are unborn Hydrocarbons (HC), Carbon monoxide (CO), Oxides of Nitrogen (NO_x), Sulfur, and solid Carbon Particulate Matter(PM). Secondly, non exhaust engine emissions which, for modern engines, can be included in two main types, evaporative emissions from fuel tank and evaporative emissions from crankcase see figure

(3.3).

Reduction of internal engines emissions is the concern of many technologies and systems. In the case of exhaust emissions, after-treatment of exhaust gases and in-cylinder reduction of emissions are of very important. The after-treatment of exhaust gases consists mainly of the use of thermal or catalytic converters and particulate traps. For in cylinder reduction, Exhaust Gas Recirculation (EGR) and some fuel additives are being tried. In the case of non-exhaust emissions, evaporation loss control systems, which aim at capturing and recirculation of the evaporated gases, are used to control evaporative loss from fuel system. In addition there are systems are used to recirculate vapors from the crankcase to the intake manifold.

In this study it is focuses on the exhaust emissions (HC, CO, and NO_x). And spark plug type and design and its effect on the amount of emissions, as contribution in global efforts to reduce internal combustion engine's emissions.

3.6 Exhaust Emissions

In this study it is focuses on two of the exhaust emissions which are HC and CO. In addition to the amounts of Carbon Dioxide (CO_2) and Oxygen (O_2) as they are inevitably emitted from internal combustion engines in practical conditions.

3.6.1 Hydrocarbon (HC)

Exhaust gases leaving the combustion chamber of an SI engine contain up to 6000 ppm of hydrocarbon components, the equivalent of 1-1.5% of the fuel. About 40% of this is unburned gasoline fuel components. The other 60% consists of partially reacted components that were not present in the original fuel. These consist of small non equilibrium molecules which are formed when large fuel molecules break up (thermal cracking) during the combustion reaction. There are several cause for the production of HC emissions :

1. Incomplete combustion
2. Crevice Volumes and flow in crevices
3. Leakage past the exhaust valve
4. Valve overlap
5. Deposits on walls
6. Oil on combustion chamber walls

Among the mentioned causes focus is paid to incomplete combustion only since it is directly related to spark plugs. Even when the fuel and air entering an engine are at the ideal stoichiometric mixture, perfect combustion does not occur and some HC ends up in the exhaust. There are several causes of this. Incomplete mixing of the air and fuel results in some fuel particles not finding Oxygen to react with.

Flame quenching at the walls leaves a small volume of unreacted air-and-fuel mixture. The thickness of this unburned layer is on the order of tenths of a mm. Some of this mixture, near the wall that does not originally get burned as the flame front passes, will burn later in the combustion process as additional mixing occurs due to swirl and turbulence.

Another cause of flame quenching is the expansion which occurs during combustion and power stroke. As the piston moves away from TDC, expansion of the gases lowers both temperature and pressure within the cylinder. This slows combustion and finally quenches the flame somewhere late in the expansion stroke. This leaves some fuel particles unreacted. High exhaust residual causes poor combustion and a greater likelihood of expansion quenching. This is experienced at low load and idle conditions. High levels of EGR will also cause this.

It has been found that HC emissions can be reduced if a second spark plug is added to an engine combustion chamber. By starting combustion at two points, the flame travel distance and total reaction time are both reduced, and less expansion quenching results.

According to what is mentioned, it is possible to find a spark plug, which have the right design and characteristics, that can create a stronger flame nucleus. With a more viable nucleus, the flame front will be developed in a shortened time. Therefore the overall reaction time can be reduced which will result in a decreased quenching effect and a consequent reduction in HC emissions see in figure (3.3).

3.6.2 Carbon Monoxide (CO)

Carbon monoxide, a colorless, odorless, poisonous gas, is generated in an engine when it is operated with fuel-rich equivalence ratio, as see in Figure (3.3). When there is not enough Oxygen to convert all Carbon to CO_2, some fuel does not get burned and some Carbon ends up as CO. Typically the exhaust of SI engine will be about 0.2% to 5% Carbon monoxide.

Maximum CO is generated when an engine runs rich, such as when starting or when accelerating under load. Even when the intake air-fuel mixture is stoichiometric or lean, some CO will be generated in the engine. Poor mixing, local rich regions, and incomplete combustion will create some CO. Since the formation of CO is strongly related to incomplete combustion regardless the air-fuel ratio, if a strong and active flame kernel is created, better combustion performance can be attained. As a result a reduction in CO emissions can be attained.

3.6.3 Oxygen (O_2)

Oxygen is basic reactant in the combustion process since it cannot occur with out Oxygen. In a stoichiometric mixture of gasoline and air and in the case of complete combustion process the whole amount of O_2 is supposed to react and end in the exhaust gases as water and Carbon dioxide. However, in real conditions perfectly stoichiometric mixtures and complete combustion are hard to be achieved. This will lead to some amounts of O_2 going outside the engine with the exhaust gases. As result, It is logical to judge the completion of combustion process by measuring the levels of O_2 in the emissions. And as mentioned before, the combustion process is controlled by the initiation of the process and flame creation; spark plug's role; hence the spark plug performance can be measured.

3.6.4 Carbon Dioxide (CO_2)

Carbon Dioxide is a natural product of the combustion reaction as it is shown in the ideal combustion equation mentioned below equation(3.1). It is simply produced when the fuel molecules in our case gasoline (C_8H_{18}) breaks and the Carbon atoms combustion with Oxygen atoms. Consequently, the efficiency of combustion process can be judged by measuring the amounts of CO_2. In other words, higher amounts of CO_2 predict better combustion. Considering the fact that the spark plug ignites the fuel in this experiment and that the whole process of combustion is controlled by the flame creation and propagation, it is possible to predict the performance of the spark plug.

$$C_8H_{18} + 12.5(O_2 + 3.76N_2) = 8CO_2 + 9H_2O + 47N_2 \tag{3.1}$$

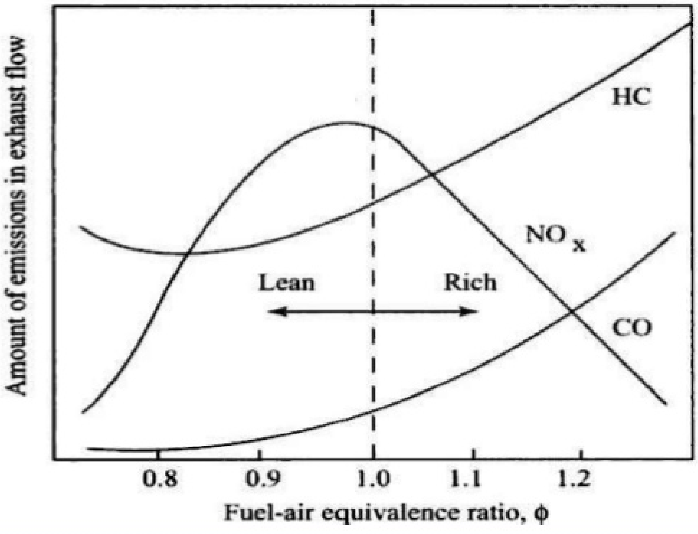


Figure 3.3: Relationship between equivalence ratio and emission concentration

Chapter 4

Test unit and equipment specifications

In this chapter, which is an electrical dynamometer figure (4.1) and its parts will be described, and the specifications of the three used spark plugs will be shown. In addition to that the experiment steps will be mentioned and the steps of using the engine cycle analyzer program will be described.

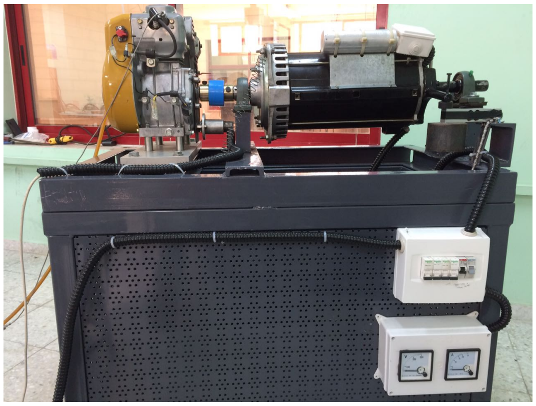


Figure 4.1: electrical dynamometer

4.1 Spark Plug

this section illustrates the specifications of the used spark plugs.Tables (4.1, 4.2, 4.3)show the specifications of the single electrode, two electrode and four electrode plugs respectively.

Table 4.1: Specification of spark plug with single electrode[3]

Description	**Current product**
center electrode core material	Copper core
electrode core material	nickel
gap size	0.028 in
ground configuration	standard
Electrode gap	0,60 mm
Ground Electrode Core Material	Nickel Core
Ground Strap Quantity	1
Manufacturer Heat Range	6
Reach	12.7 mm
Resistor	Yes
Seat Type	Gasket
Thread Diameter	14 mm
Tip Configuration	Loose
Wrench Diameter	13/16 in

Table 4.2: Specification of spark plug with two electrode[2]

Description	Current product
Center Electrode Tip Material:	Nickel-Yttrium
Gap Size:	.9
Ground Configuration:	Multiple
Ground Electrode Core Material:	N/A
Ground Electrode Quantity:	2
Ground Electrode Tip Design:	Multiple
Hex Size:	16
Insulator Material:	Ceramic
Insulator Type:	Projected
Manufacturer Heat Range:	7
Outdoor Power Equipment Application:	No
Reach:	19
Seat Type:	Flat

Table 4.3: Specification of spark plug with four electrode[2]

Description	Current product
Independent aftermarket part (IAM)	0242242801
designation Spark-plug set,	Super 4
Type formula	FR 56
Search number (KSN)	512
Marketing number	512
Spark position	4 mm
Electrode gap	b0,90 mm
Thread pitch	1,25 mm
Thread length	19,0 mm
Width across flats	16,0 mm
Center electrode core material	CrNi+Cu
Center electrode material	CrNi
Ground electrode material	CrNi
Sealing seat	flach verformbar
Type of connection	Detachable DIN/SAE nut
Interfer. supp./burn-off res.	6 kOhm
Tightening angle	90 °
Tightening torque	28 Nm

4.2 Test unit

The test unit used in this project consists of a one cylinder, 4-stroke, carburetor gasoline internal combustion engine equipped with an incremental encoder and pressure sensors. These sensor are connected to the engine cycle analyzer, which is used with the Tecquipment ECA100 to view The engine. the engine is used to operate an AC generator, The generator is connected to the load unit. Which consist of five thermal resistors, the power of each one is 600 watt.The following block diagram see figure (4.2) describes the basic parts of the system and how they are connected.

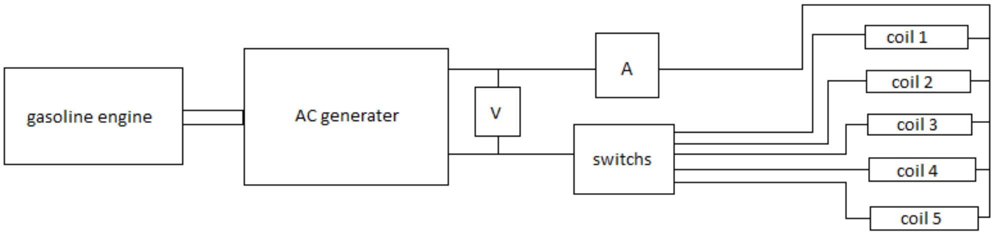


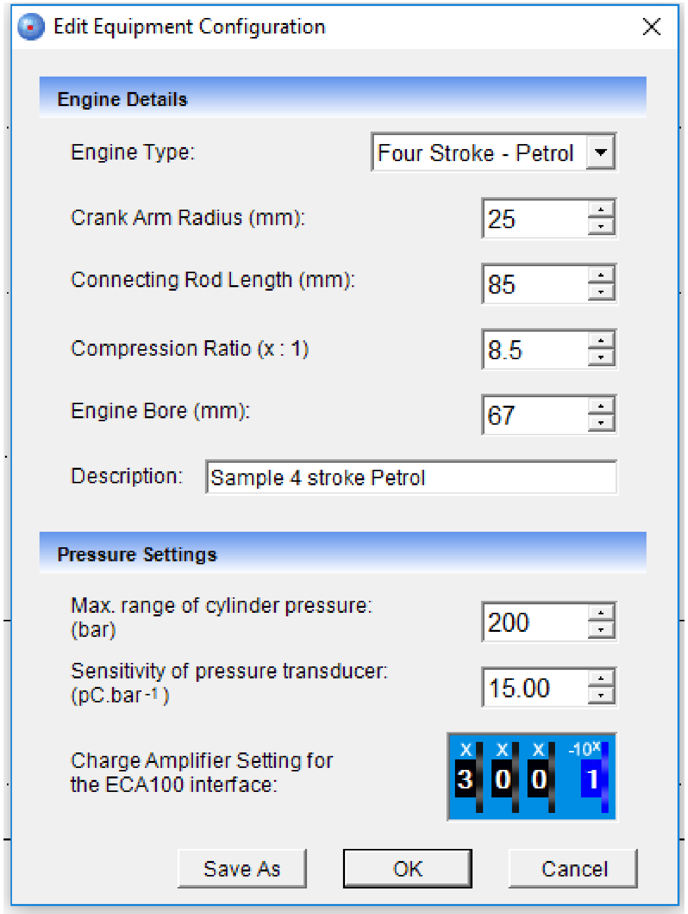
Figure 4.2: Block diagram of the system

Table 4.4: Engine Specification

Item	**Specification**
Dimension (when fitted to base plate)	w 400 mm H 400mm D 300mm
net weight (with base plate)	20Kg
fuel type	petrol (gasoline)
fuel tank	red- painted steel with vent and filler cap
exhaust outlet	nominally 1” BSP
ignition system	electric
absolte maximum power	4.4KW at 4000RPM
continuous rated power	2.6 KW at 3000 RPM 2.9 KW at 3600 RPM
bore	67 mm
stroke/crank radius	49 mm/24.5mm
connecting rod length	85 mm
engine capacity	$172cm^3$(0.172L)
compretion ratio	8.5:1
oil type	SAE 20, SAE 30 or multigrade 10W-30
oil capacity	0.62 litre

4.3 Steps of Experiment

1. Calibration of the Engine Cycle Analyzer by editing the engine specifications in the program see in the Fig (4.3). Then the calibration of the gas analyzer used to measure the amounts off emissions by applying the leak test which is automatically required by the device and then the device continues to do calibration automatically without any intervention.



Engine Details

Engine Type: Four Stroke - Petrol

Crank Arm Radius (mm): 25

Connecting Rod Length (mm): 85

Compression Ratio (x : 1) 8.5

Engine Bore (mm): 67

Description: Sample 4 stroke Petrol

Pressure Settings

Max. range of cylinder pressure: (bar) 200

Sensitivity of pressure transducer: (pC.bar $^{-1}$) 15.00

Charge Amplifier Setting for the ECA100 interface: x x x -10^x 3 0 0 1

Figure 4.3: Calibration of engine cycle analyzer

2. The engine is operated until it became warm.
3. After warming the engine it is turned off.
4. The piston is set in TDC by rotating the crank shaft coupling see in fig (4.4), while pressing the (set TDC) button see in fig (4.5). then the rest is pressed.

Figure 4.4: Coupling

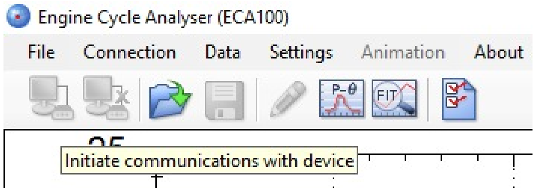
Figure 4.5: Set TDC button and Rest

5. The engine speed is controlled by the throttle valve and fuel valve.

6. The load is controlled by the switches see in figure (4.6). then load is increased gradually

Figure 4.6: Switches

7. The program is connected to the ECA100 to capture the sensor readings by pressing the connect button then the record data button see in fig (4.7)



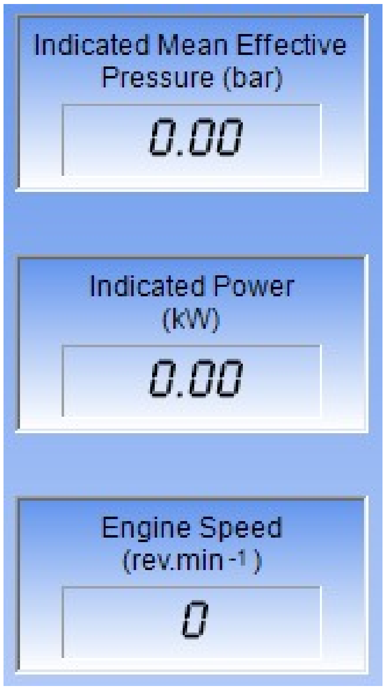
Initiate communications with device

Figure 4.7: Connect icon

8. The current and voltage consumed by the load are read from the ammeter and voltmeter see in figure (4.8)

Figure 4.8: Ammeter and Voltmeter

9. The maximum pressure, indicated power, Indicated mean effective pressure and engine speed are read from the computer see fig (4.9)



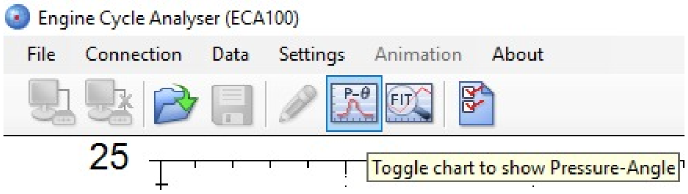
Indicated Mean Effective Pressure (bar)
0.00

Indicated Power (kW)
0.00

Engine Speed (rev.min^{-1})
0

Figure 4.9: Indicated power, mean effective pressure and engine speed

10. The p-v and p-α diagram are recorded on the computer using the program (engine cycle analyser)and it is toggled between them by the toggle button see in figure (4.10).



Toggle chart to show Pressure-Angle

Figure 4.10: Toggle icon between p-v and p-α

11. Each spark plug is tested at a load of 1200W and 2400W see in figure (4.11).

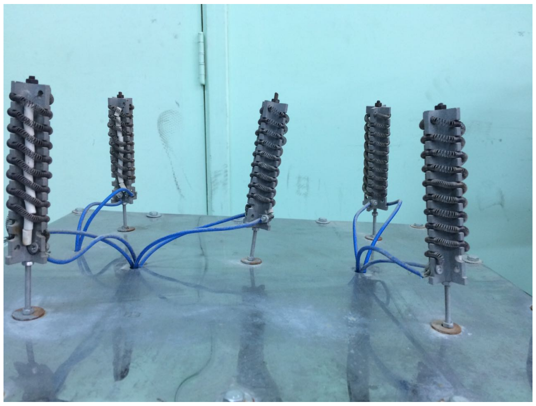


Figure 4.11: Loads

Chapter 5

Data and Analyses

all experiments were performed at internal combustion engine laboratory at mechanical department engineering at ppu

5.1 P-v and P-α

In this section the P-V and P-α curves were used to find the maximum pressure which measures the plug performance. The indicated power and mean indicated effective pressure were combined in this section for the same purpose.

Using the p-α curves, the maximum pressure was found and used to indicate the combustion quality in a way that higher maximum pressures mean higher combustion quality and lead to better engine performance. This was used to predict that the plug have better performance .In addition to that the values of indicated power and the mean indicated effective pressure were used in a way that the higher they are the better the plug performance due to the direct connection between the plug performance, combustion quality and engine performance.

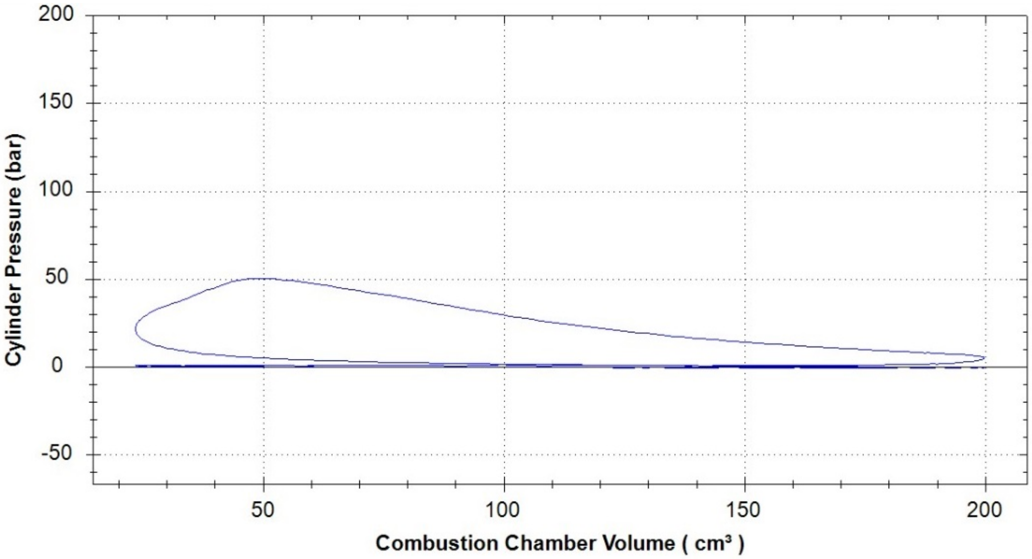


Figure 5.1: PV one electrode at 2300rpm

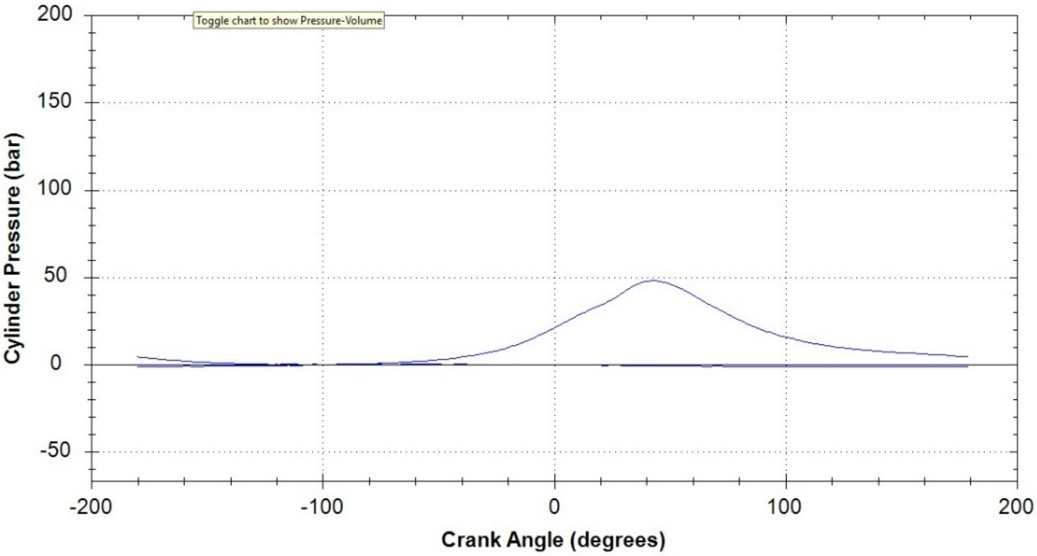


Figure 5.2: $P\alpha$ one electrode at 2300rpm

the P-V and P-α diagrams ware used on this experiment to insure the proper operation of the engine and to collect the maximum pressure data.While running the engine on one electrode spark plug, the P-V diagram shown at figure (5.1) shows a correct auto cycle which means that the engine was working correctly. And the P-α diagram shown in figure(5.2) was used to get the maximum pressure value which is 50 bar at 2300 rpm.

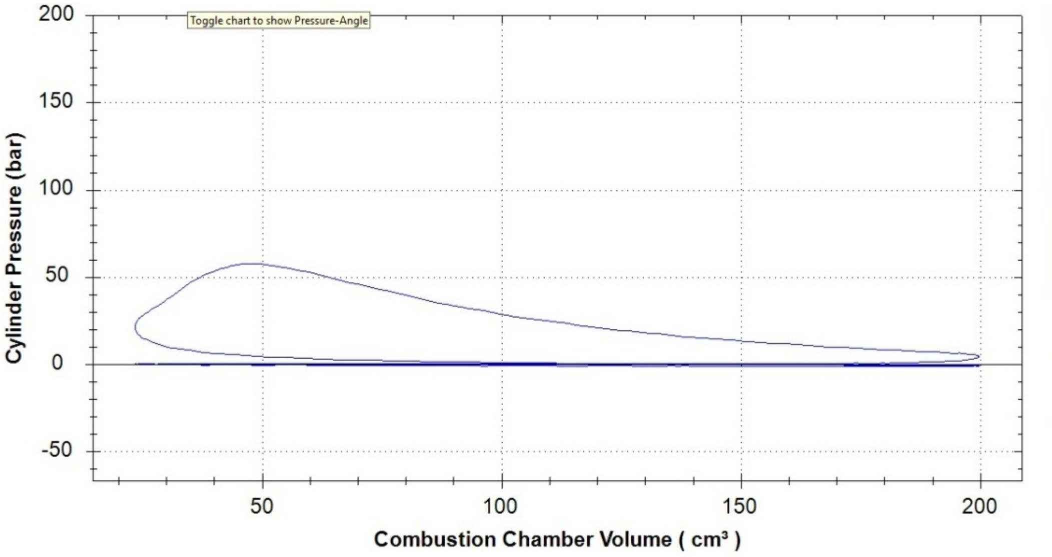


Figure 5.3: PV two electrode at 2300rpm

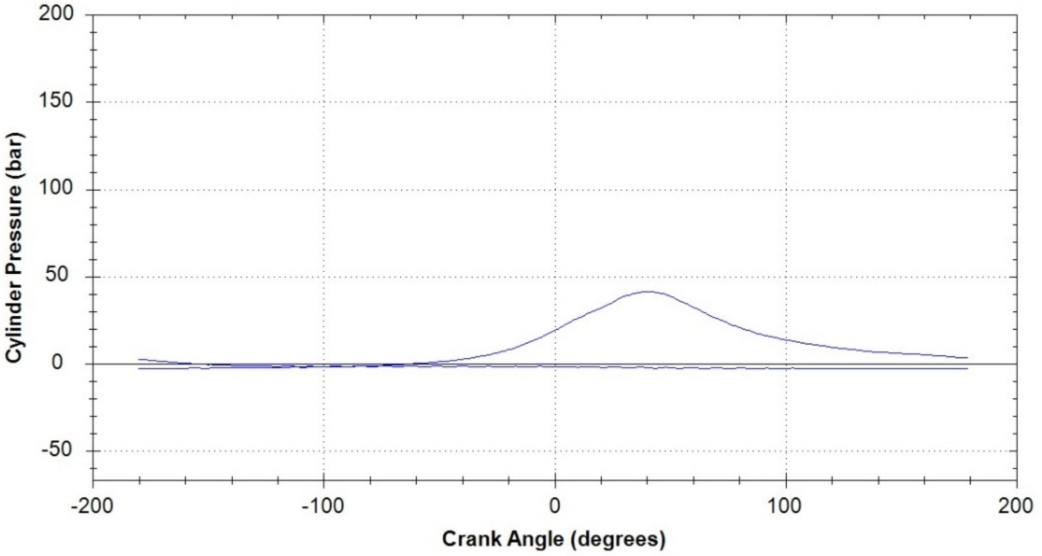


Figure 5.4: $P\alpha$ two electrode at 2300rpm

While running the engine on two electrode spark plug, the P-V diagram shown at figure (5.3) a correct auto cycle which means that the engine was working correctly. And the P-α diagram shown in figure (5.4) was used to get the maximum pressure value which is 40 bar at 2300 rpm.

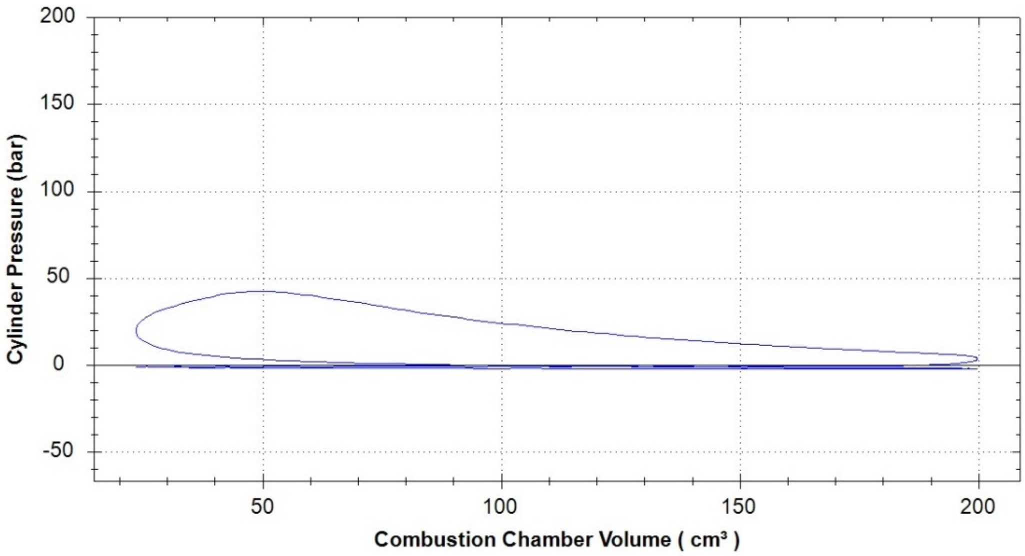


Figure 5.5: PV four electrode at 2300rpm

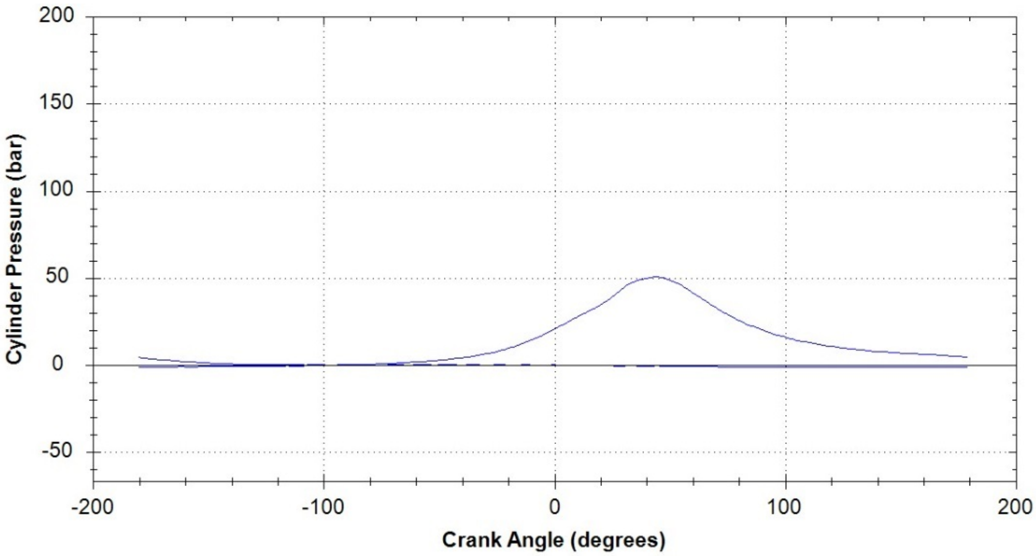


Figure 5.6: $P\alpha$ four electrode at 2300rpm

While running the engine on four electrode spark plug, the P-V diagram shown at figure (5.5) shows a correct auto cycle which means that the engine was working correctly. And the P-α diagram shown in figure (5.6) was used to get the maximum pressure value which is 52 bar at 2300 rpm.

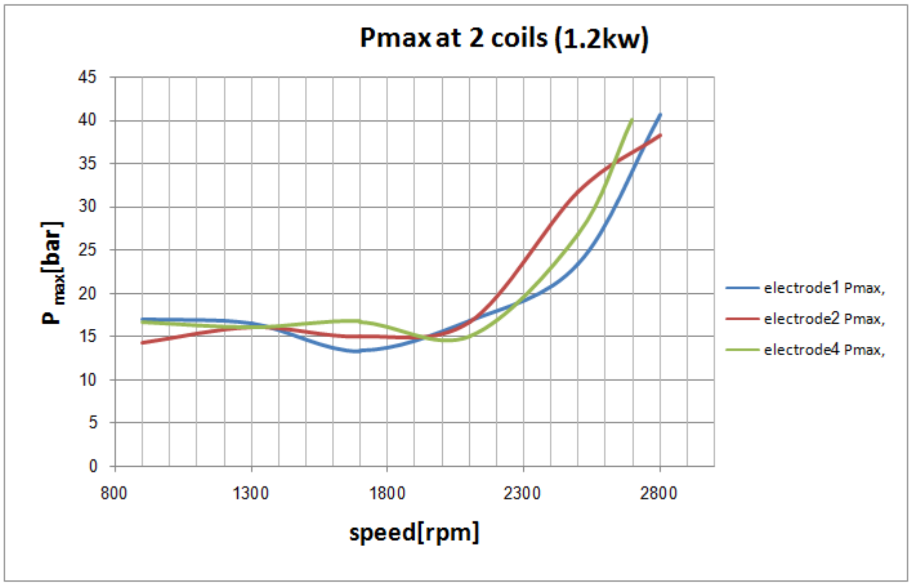


Figure 5.7: Maximum pressure values at a load of two coils

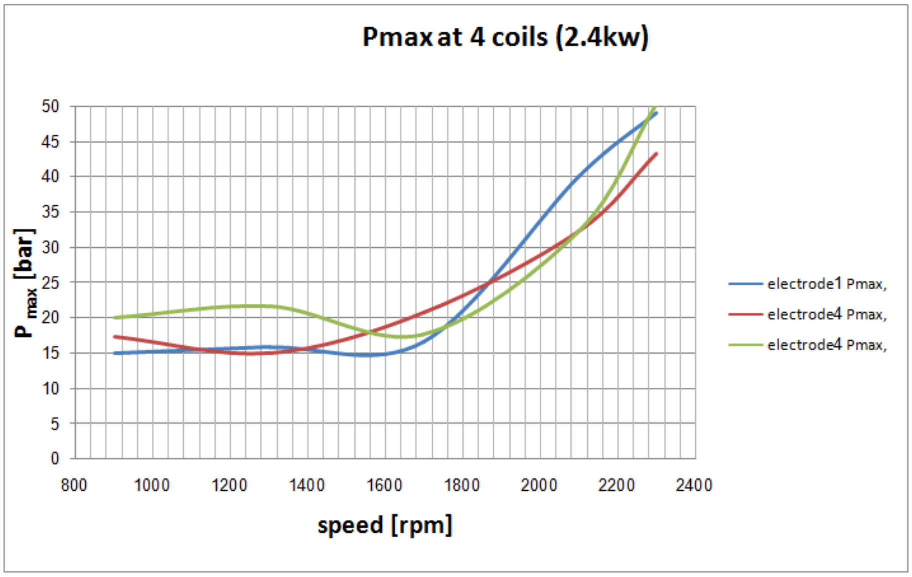


Figure 5.8: Maximum pressure values at a load of four coils

figures (5.7, 5.8) show that the maximum pressure values were almost the same operating any of the three spark plugs.And they are almost steady at low speeds. However, the pressure values rise rabidly at about 2000 rpm. at 1.2 kW the two electrode plug gave the highest average maximum pressure, on the other hand, at 2.4 kW the four electrode plug gave the highest average maximum pressure.

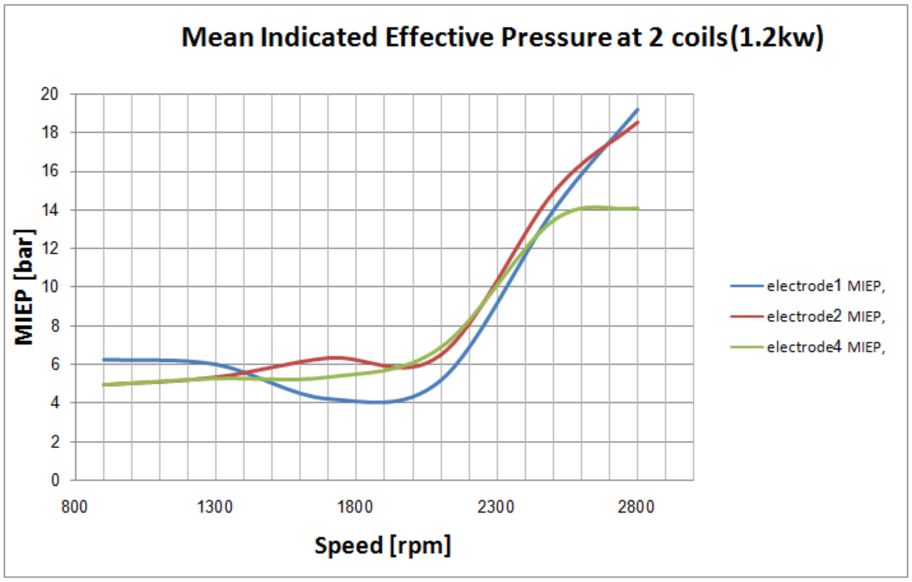


Figure 5.9: Mean Indicated Effective Pressure values at a load of two coils

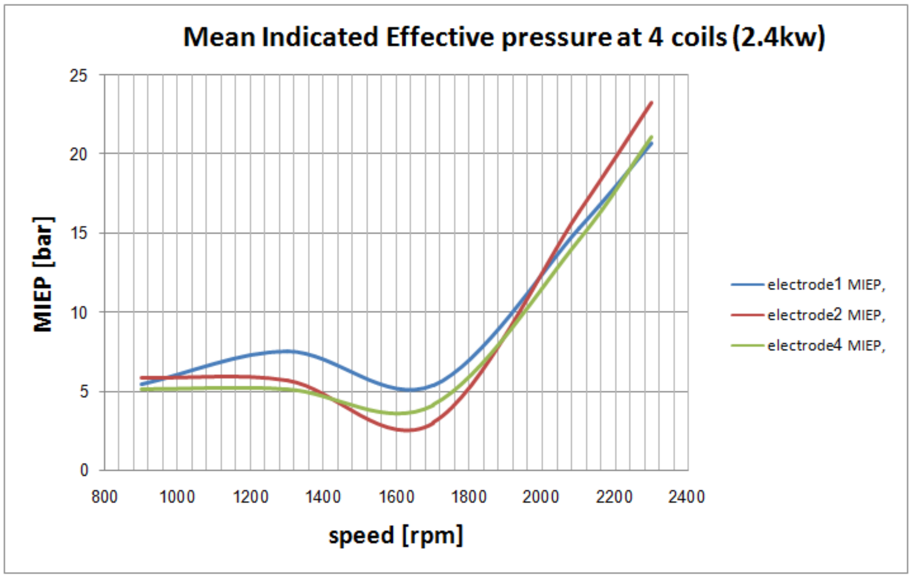


Figure 5.10: Mean Indicated Effective Pressure values at a load of four coils

figures (5.9, 5.10) show that the Mean Indicated Effective Pressure values were almost the same operating any of the three spark plugs. The values rised a little from 900 - 1300 rpm, Then they fall down from 1300 - 1700 rpm. After that they rised rabidly.the highest average value at 1.2 and 2.4 kW was given by two electrode plug.

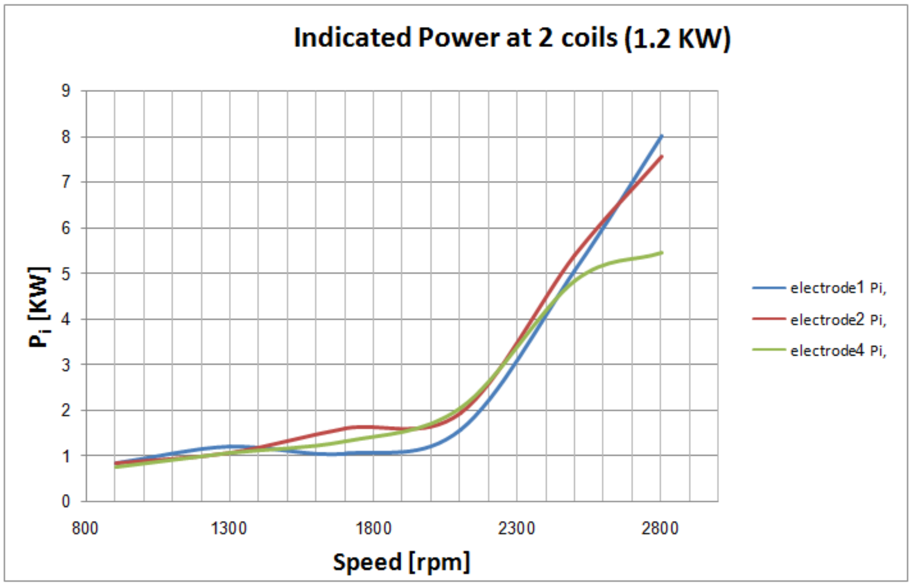


Figure 5.11: Indicated power values at a load of two coils

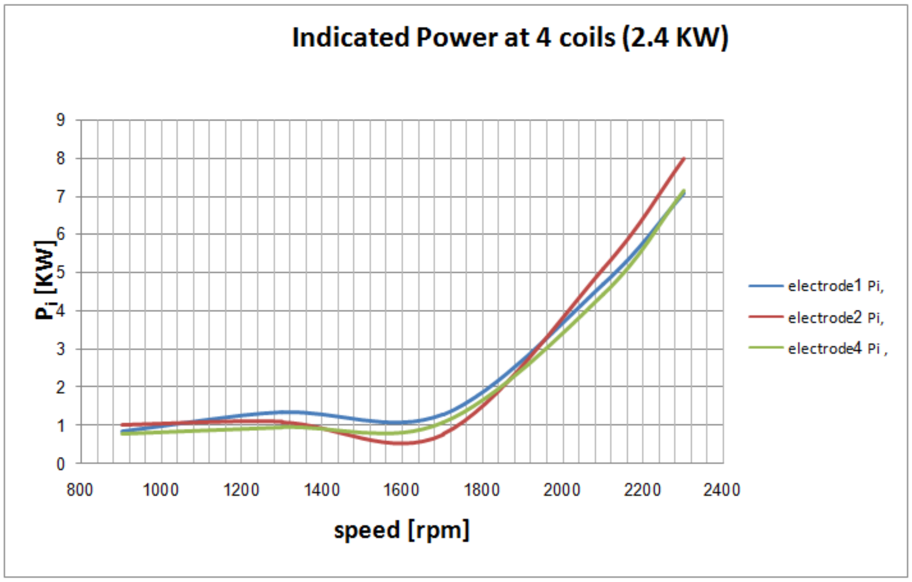


Figure 5.12: Indicated power values at a load of four coils

figures (5.11, 5.12) show that the Indicated power values were almost the same operating any of the three spark plugs. The values rised a little from 900 - 1300 rpm, Then they fall down from 1300 - 1700 rpm. After that they rised rabidly.the highest average value at 1.2 and 2.4 kW was given by two electrode plug.

Table 5.1: Average of maximum pressure and maximum power

	Two coils (1.2 KW)		
	avg P_{max}(bar)	avg MIEP(bar)	avg Pi (KW)
1 electrode	21.25	9.13	2.97
2 electrode	22	9.405	3.083
4 electrode	21.85	8.33	2.58

Table 5.2: Average of maximum pressure and maximum power

	Four coils (2.4 KW)		
	avg P_{max}(bar)	avg MIEP(bar)	avg Pi (KW)
1 electrode	27.32	10.78	3.05
2 electrode	25.72	10.84	3.19
4 electrode	28.4	10.05	2.88

In the tables (5.1, 5.2), the averages of maximum pressure, Indicated power and the Mean Indicated Effective Pressure is shown. These values were compared and studied in order to find the superiorities of the tested spark plugs.

The Mean Indicated Effective Pressure and Indicated Power were given the most part of attention because they can give direct implications about the engine performance. The measured values were analyzed and understood in a way that higher values of pressure and power mean better performance of the spark plug that lead to better performance of the engine.

It was noticed that the two electrode plug gave the highest level of power at high and low loads. It was also found that the four electrode plug produced the lowest power at the low and high loads which indicate lower combustion quality and hence a low plug performance. It was also noticed that the one electrode plug produced medium level of power and emissions at the two loads.

5.2 Emission

Emissions quantities and reduction of emissions is one of the most important considerations in the modern automotive industry. In this section the emissions data is shown and analyzed to determine the performance plugs see in figure (5.13).

Figure 5.13: Emission analyzer

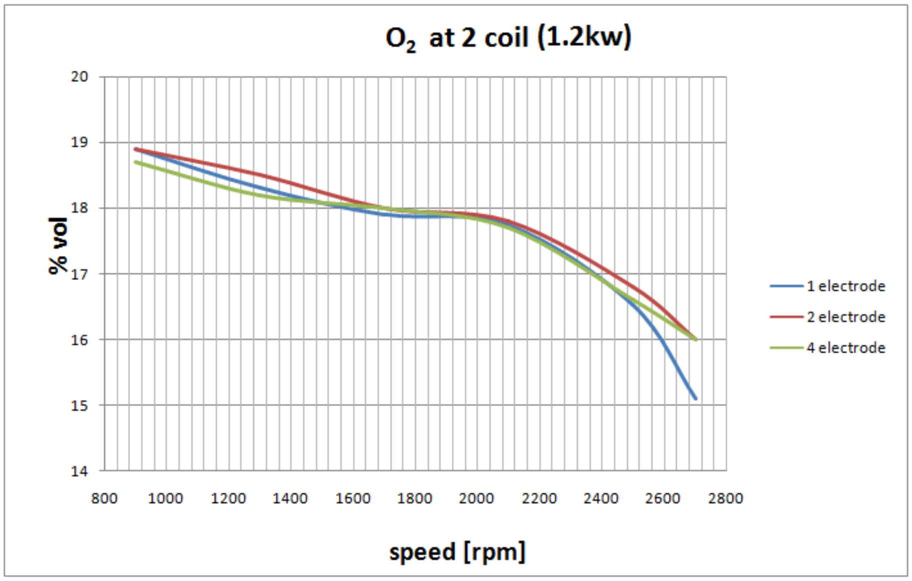


Figure 5.14: Oxygen amounts at a load of two coils

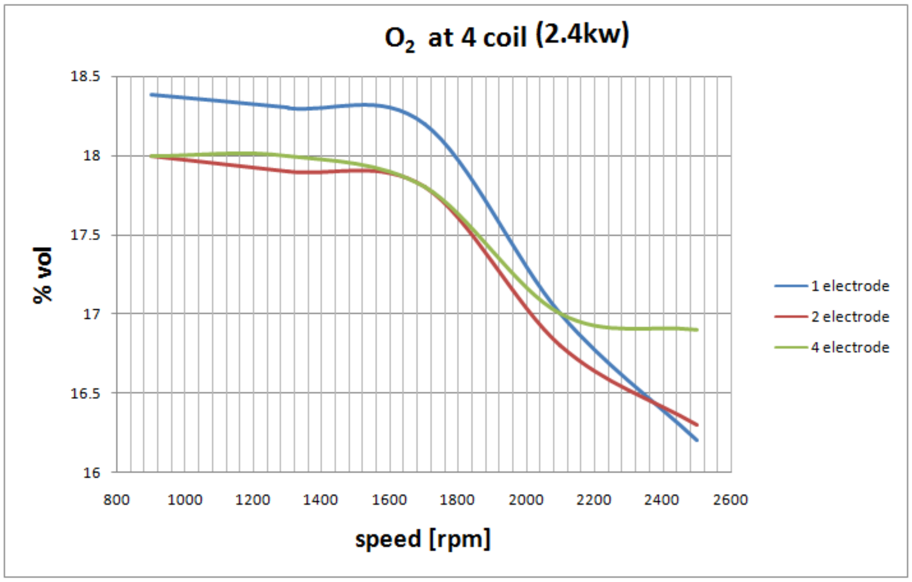


Figure 5.15: Oxygen amounts at a load of four coils

From figure (5.14, 5.15) it is noticed that the amounts of o2 the exhaust are very close to each other and thy fall down during whole range of speeds. the minimum average value at one electrode plug at 1.2 kW. However, at 2.4 kW the minimum average value was given by the four electrode plug.

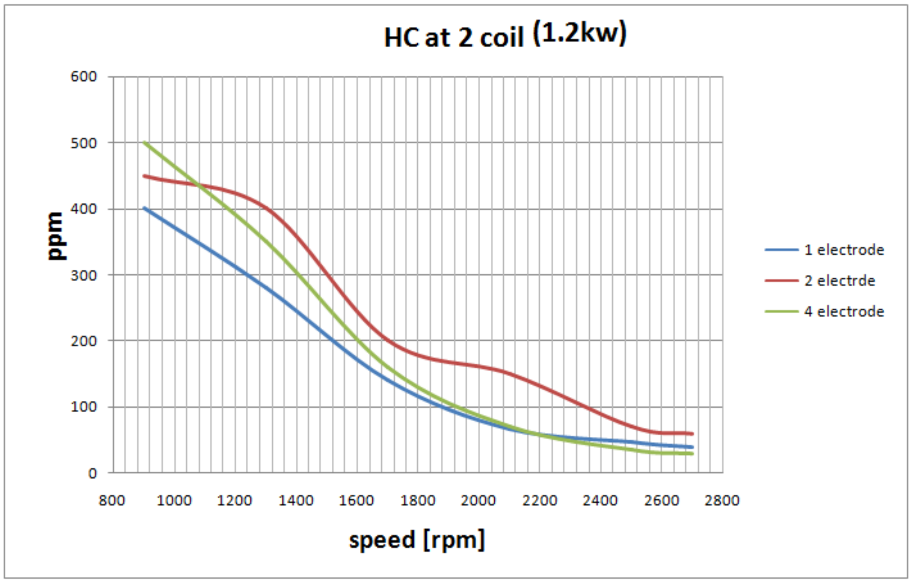


Figure 5.16: Hydrocarbons amounts at a load of two coils

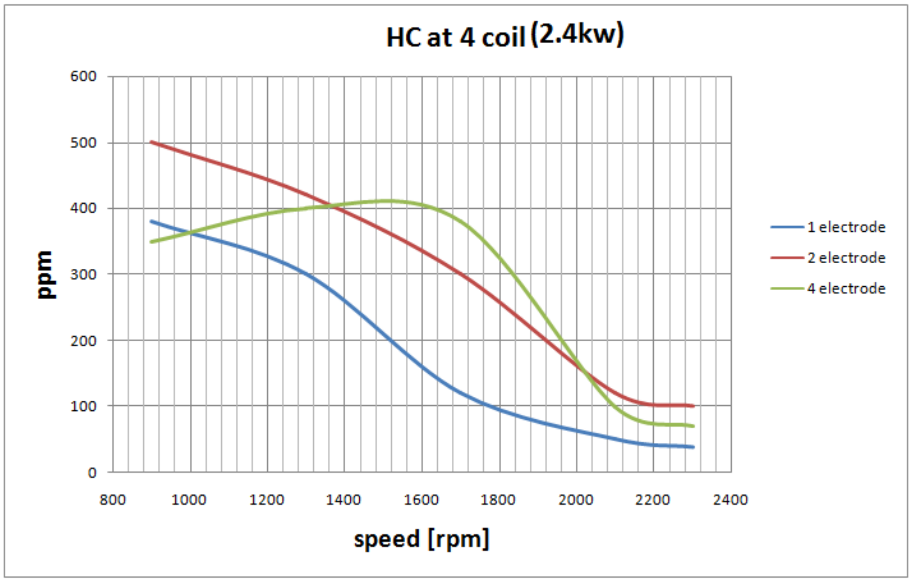


Figure 5.17: Hydrocarbons amounts at a load of four coils

Figure (5.16) shows that amounts of HC was falling down through the experiment at 1.2 kW. On the other hand figure (5.17) the amounts of HC was falling down steadily using the one and two electrode plugs. But using the four electrode plug the HC amounts rised from 900 - 1600 rpm and then falling down to 2200 rpm. the minimum value of HC on 1.2 and 2.4 kW was produced by one electrode

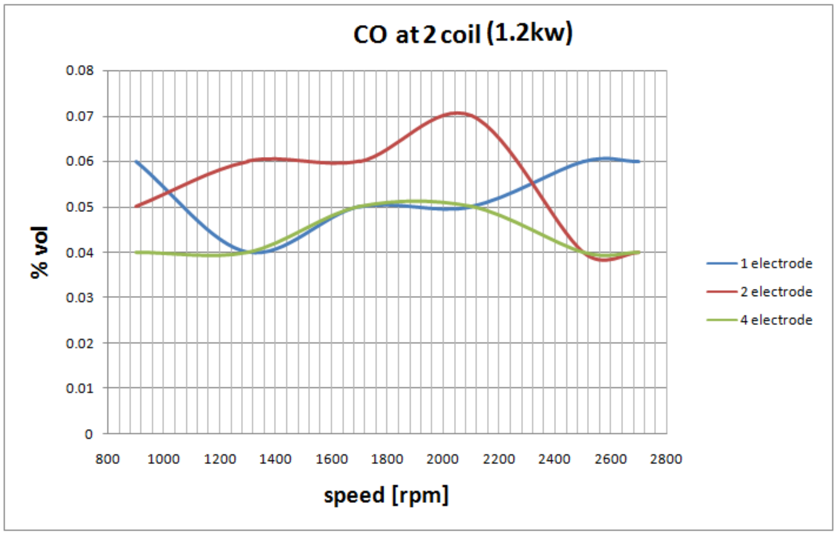


Figure 5.18: Carbon monoxide amounts at a load of two coils

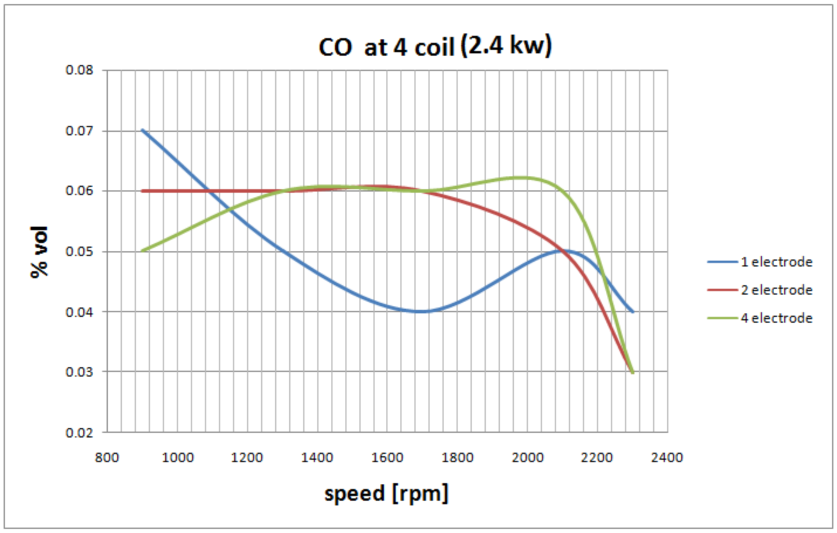


Figure 5.19: Carbon monoxide amounts at a load of four coils

In figures (5.18,5.19), the CO amounts are shown. In the figure (5.18) at 1.2 kW the amounts were fluctuating greatly between the range of (0.04 - 0.05)% vol with increasing speed. It is noticed that minimum average amount of CO was produced using the four electrode plug. However, In figure (5.19) at 2.4 kW the values were fluctuating in the range of (0.04 - 0.06) % vol, and the minimum average amount was produced using the one electrode plug. It is is also noticed that the CO amount were almost equal at the two loads and didnt range alot with changing spark plug

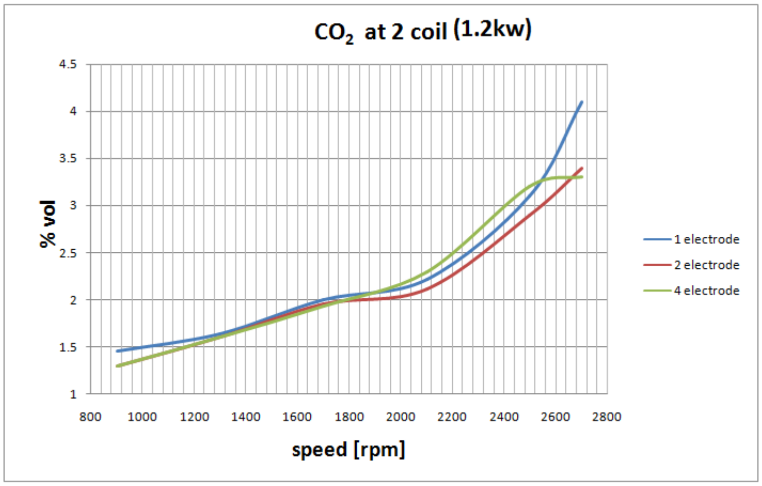


Figure 5.20: Carbon dioxide amounts at a load of two coils

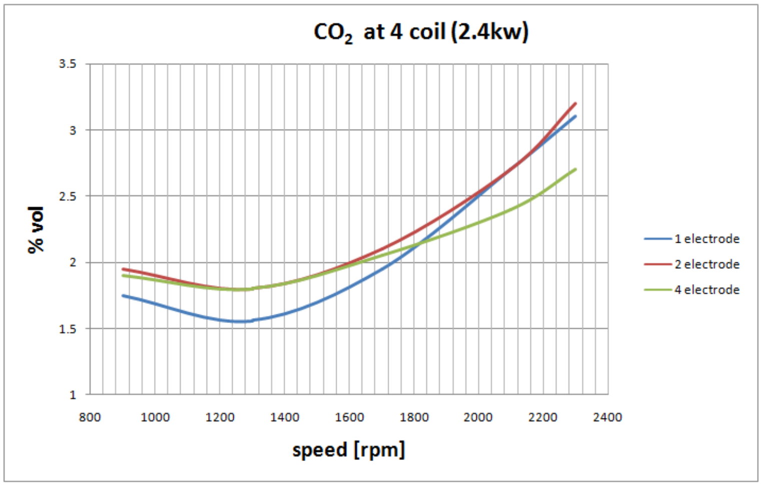


Figure 5.21: Carbon dioxide amounts at a load of two coils

figure (5.20) shows the amounts of CO_2 in the emissions at 1.2 kW. It is noticed that the amounts of CO_2 rise while increasing engine speed. And the maximum average amount of CO_2 was produced by one electrode spark plug. Figure (5.21) shows the amounts of CO_2 at 2.4 kW. They decrease from 900 - 1300 rpm and increase from 1300 - 2200 rpm. And the maximum average amount of CO_2 was produced by two electrode plug.

Table 5.3: Average of emission amounts

	2 coils (1.2 KW)			
	avg CO (% vol)	avg CO_2 (% vol)	avg HC (ppm)	avg O_2 (% vol)
1 electrode	0.053	2.42	162.17	17.41
2 electrode	0.053	2.21	221.67	17.67
4 electrode	0.03	2.27	190.83	17.53

Table 5.4: Average of emission amounts

	4 coils (2.4 KW)			
	avg CO (% vol)	avg CO_2 (% vol)	avg HC (ppm)	avg O_2 (% vol)
1 electrode	0.05	2.21	177.6	17.62
2 electrode	0.052	2.35	288	17.63
4 electrode	0.052	2.17	260	17.54

In these tables (5.3, 5.4), the averages of amounts of emissions were mentioned. The data were understood in a way that higher amounts of CO_2 indicate that better combustion occurred and the same is indicated if less HC and O_2 were emitted since both of these reactants will be consumed in the combustion reaction to produce CO_2. The CO amount were not give that attention since its values was fluctuating. However it was found that CO emissions increased with the spark plugs that produce higher levels of powers.

The engine produced the highest emissions at the low load using the two electrodes spark plug which may indicate lower quality of combustion or higher fuel consumption. On the other hand, the quality of emissions was lower at high load. whereas the engine produced medium amounts of emissions while operating on the four electrodes spark plugs.

5.3 Conclusion

- It was found that the two electrode plug gave the highest level of power at the two loads which indicate better combustion quality, the better combustion quality can be referred to better spark distribution by the two electrodes. However the engine produced the highest emissions at the low load using this plug which may indicate lower quality of combustion or higher fuel consumption. On the other hand, the quality of emissions was better at high load.
- It was also found that the four electrode plug produced the lowest power at the low and high loads which indicate lower combustion quality. Here, the bad combustion quality is reasonable due to the number of electrode which can easily lead to high quenching effect and restricting flame propagation. Meanwhile, the engine produced medium amounts of emissions while operating on this plug.
- It was also noticed that the one electrode plug produced medium level of power and emissions at the two loads. This indicate medium combustion quality. The medium combustion quality can be explained knowing that the one electrode plug uses the gap concept which restrict the spark path in one direction compared with the surface gap concept used in the two electrode plug which gives the spark two paths to flow.
- The main difference between the used plugs was the number of electrodes and the gap size. It was found that increasing number of electrodes increases the quenching effect and reduces the plug performance. It was also noticed that reducing the gap size increases the quenching effect. With respect to these information the plug with 2-electrodes and a gap size of 0.9mm gave the best performance. While the plug with 1-electrode and gap size of 0.6mm gave medium performance. And the plug with 4-electrodes and a gap of 0.9mm gave the worst performance.

5.4 Recommendation

- It is recommended to fix the experimental engine on a more rigid stand and provide the unit with proper rubber mounts in order to reduce noise pollution and damp vibrations.
- It is recommended to renew the outer part of the crankshaft and the generator shaft and to use proper connection that fits the shafts after lathing
- It is recommended to equip the lab with a strong air blower to refresh the air inside, especially that the engine is operated in a closed area.
- It is recommended to add more sensors on the device like knock sensors and temperature sensors.
- It recommended to use a gas analyzer that measures the amount of NOx for more precise evaluation of emissions.

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[1] Spark plug technical information (whitepaper) @ONLINE, December 2016.

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