

## Effect of electrode erosion on the required ignition voltage of spark plug in CNG spark ignition engine

S. Javan<sup>1\*</sup>, S.V. Hosseini<sup>2</sup>, S.S. Alaviyoun<sup>3</sup>, F. Ommi<sup>4</sup>

<sup>1</sup>Irankhodro Powertrain Comapany (IPCO), Tehran, Iran, [s.javan@ip-co.com](mailto:s.javan@ip-co.com)

<sup>2</sup>Irankhodro Powertrain Comapany (IPCO), Tehran, Iran, [v.hosseini@ip-co.com](mailto:v.hosseini@ip-co.com)

<sup>3</sup>Irankhodro Powertrain Comapany (IPCO), Tehran, Iran, [sh.alaviyoun@ip-co.com](mailto:sh.alaviyoun@ip-co.com)

<sup>4</sup>Tarbiat Modares University, Tehran, Iran, [fommi@modares.ac.ir](mailto:fommi@modares.ac.ir)

\*Corresponding Author, Phone Number: +98-912-5611647

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### ABSTRACT

In this article, the electrode erosion and the gap growth of spark plugs were measured on of a CNG fueled engine after durability tests. Then, the required ignition voltage and the spark quality were investigated by a spark plug test rig. Considering results of measurements, the gap growth increased as the running time increased. Thus, the gap growth of spark plugs with 200 and 280 hours running time were 2 and 4.4 times more than the gap growth of spark plugs with 80 hours running time. Results of the voltage test show that the required voltage is increased with the pressure. The required voltage at 9 bar was 2 times higher than 1 bar. The increase of the required voltage and the adverse effect on the spark quality due to the gap growth are due to more running time. Accordingly, the required voltage was increased 11% at 5 bar while the gap growth was 20%. Comparing results of new and used spark plugs showed that in addition to the gap growth, deposits on the electrodes surface could lead to increase the required voltage.

## 1) Introduction

The required ignition voltage on each engine depends on operation conditions, the fuel type and the geometry of electrodes. The spark delivers the electrical energy to the mixture and ignites it. The battery supplies the primary energy of the spark and the ignition coil intensifies the voltage to supplying the required voltage. The importance of the spark in the combustion and the engine performance is a cause of many different researches about the spark and its process. The required ignition voltage and its variations during the spark, the current, the duration and the energy of the spark are physical aspects that were investigated by researchers. The electrical spark contains three phases namely: the breakdown, high current arc discharge and low current glow discharge [1]. In the breakdown, the electrical field builds up between electrodes and intensifying of the electrical field accelerates electrons toward the ground electrode. The study of voltage variations showed that the required voltage has the maximum amount in this step [2]. The breakdown is followed by high current arc discharge. This phase lasts more than the breakdown and has an important effect on the electrode erosion [1-6]. Next, the current transits to low current glow discharge. This phase has higher voltage but the current drops from 50-100 mA down to zero [3].

Considering results which published by Maly [4-5], the breakdown has more effect on the combustion process. Lee *et al.* [6] investigated the voltage and the electrical energy that discharged during a spark. The results of this research imply that the voltage and the current depend on many factors such as the spark plug gap, the internal resistance of the spark plug and the pressure (the pressure of the gas within the spark plug gap). The spark duration decreases by the increase of the spark plug gap and the pressure. Also, the discharged energy increases with the rise of the pressure [6]. According to the Paschen law, the spark plug gap and the pressure have direct effects on the required ignition voltage. The approximate estimate of the breakdown voltage ( $V$ ) in the air could be obtained from Equation 1 [6].

$$V = 30Pd + 1.35 \quad (1)$$

In this relation,  $d$  is the spark plug gap in centimeter and  $P$  is the pressure in atmospheres. The increase of the engine compression ratio has been caused to the increase of the pressure in the combustion chamber and considering Equation 1, the increase of the required voltage. According to Equation 1, by decreasing the spark plug gap, the required voltage decreases. But it is necessary to point that if the electrodes design has not been improved, decreasing the gap leads to decline of the spark plug performance during the operation with lean mixtures [6].

The required voltage depends on the mixture composition, too. The air fuel ratio varies according to the fuel type. Therefore, the electrical conductivity of different fuels is not the same. For examples, in comparison to the gasoline, the required voltage increases while the engine operates with the compressed natural gas (CNG) [7-8]. The electrode shape is another parameter that has considerable effects on the required voltage. Regarding to the published results, the miniaturized center electrode reduces the required voltage [9-10]. In addition, miniaturizing of the ground electrode has the same effect. Since, the strength of the electrical field in the spark plug gap intensifies by fine electrodes [11-12]. There is a limitation here; the energy concentration on the electrode tip leads to the rise of the electrode temperature which concludes to the acceleration of the electrode erosion rate and the decrease of the spark plug lifetime [10-11]. Hence, precious metals such as platinum, tungsten and iridium should be used to made electrodes which conclude to higher manufacturing costs [13-14].

The spark plug suffers high pressures and temperatures in the combustion chamber. These conditions lead to the electrode erosion. As the spark plug gap increases by the electrode erosion, the required voltage increases, too [14-16]. The supply voltage of the ignition coil has certain limits, hence the gap growth could increase the required voltage to quantities over than the maximum supply voltage which is a cause of the misfire. To ensure reliable sparks in various operation conditions, the maximum required voltage should be about 5 kV lower than the supply voltage of coils [15-18]. This value is called the voltage reserve which is an important parameter that confines the spark plug lifetime.

The required voltage for the CNG is higher than the gasoline. On the other hand, the electrode erosion rises while the engine operates with the CNG. Thus, the probability of the rise of the required voltage over the allowable range increases. It is obvious that this voltage should be supplied by the ignition coil. Although the rise of the required voltage may not lead to the misfire, but it could damage the ignition system.

Due to the lack of studies about the ignition system and the spark plug of CNG engines and also considering the electrode erosion, coil properties, it is necessary to study the increase of the required ignition voltage and the spark quality of spark plugs (that have been used in CNG fueled engines). Considering a large usage of nickel-based electrodes in common spark ignition engines, in this research, the electrode erosion and the gap growth of spark plugs in CNG engines has been measured during the endurance test. Then, the effect of the gap growth on the required voltage and the spark quality has been investigated. Moreover, new relations to evaluate

used plugs of the CNG engine have been extracted with the aid of the prepared test rig.

## 2) Experimental methods

To implement this research, six sets (24 numbers) of the spark plug which are recommended by the engine manufacturer prepared at first. Next, the cap diameter and the length of the central electrode and also the thickness of the ground electrode were measured by the profile projection. Five sets of the spark plug had been used in the endurance test and the rest used for the comparison in the voltage test. J-type conventional spark plugs with nickel-based electrodes are used in this research. The gap size and dimensions of electrodes is presented in Table 1.

Table 1: Averaged gaps and electrode dimensions of tested spark plugs

No.	Characteristic	Dimension
1	Gap size (mm)	0.87
2	Length of center electrode (mm)*	1.48
3	Diameter of center electrode (mm)	2.80
4	Thickness of ground electrode (mm)	1.32

\*Protrusion of center electrode from insulator nose.

Experiments were performed using a 4-stroke naturally aspirated engine. Specifications of this CNG engine are presented in Table 2. The installation of the engine in the test cell and variations of the engine torque during a cycle of the endurance test are shown in Figures 1 and 2, respectively. The engine speed varies from 850 rpm (as the idle speed) to 5300 rpm with same ramps. Thus, in more than 77% of each cycle, the engine has been run with 5300 rpm under full load conditions. To visual investigation of the electrode erosion, pictures were taken by the Mitutoyo PJ-2500 profile projection. These pictures enable us to compare spark plugs before and after of the endurance test. The profile projection is shown in Figure 3.

Table 2: Specifications of the tested engine

Cylinders	4
Fuel type	CNG
Arrangement	Inline
Bore	87.34 mm
Stroke	70.8 mm
Compression ratio	1:10.8
Displacement Volume	1696 cm <sup>3</sup>
Maximum power	62.5 kW @ 5000 rpm
Maximum Torque	138 N.m @ 3000 rpm
Idle Speed	850 rpm
Maximum Speed	6400 rpm

To investigation the effect of running time on the electrode erosion and required voltage, spark plugs used with various running times (80-280 hours) in endurance tests. Gap size and electrode dimensions measured again after endurance tests. Next, sparking quality and required voltage of spark plugs evaluated by spark plug test rig. This test rig and its components are shown in Figure 4.



Figure 1: The tested engine in the test cell

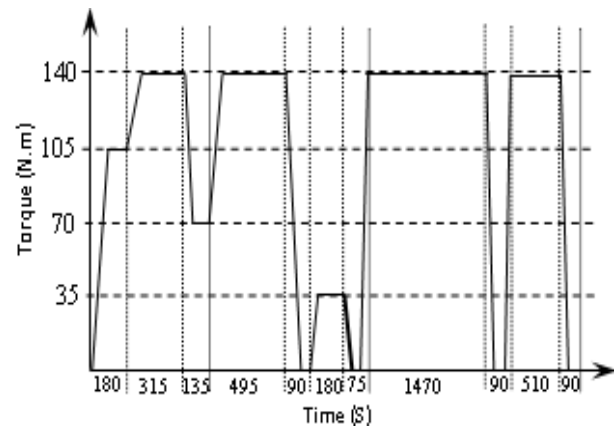


Figure 2: Engine torque variations during a cycle of the endurance test

The main part of this setup is a constant volume chamber with 7 cm diameter inside and capped with 2.5 cm thickness quartz window at one end. The sparking quality was studied visually through this quartz window.

Pressure and temperature sensors are located in the chamber. To eliminate the oxidation of electrodes, nitrogen was used to pressurize the chamber. The chamber has been filled by nitrogen and therefore, there was no gas motion around the spark plug gap. Original engine components are used in this test rig, e.g. the ignition coil is the same as the coil of the engine which triggered with the actual coil driver that had been used in the ECU. The engine uses a distributor, therefore, this system has been used in the test rig.

The required voltage was measured by the Tektronix P6015A high voltage probe. This probe can measure DC voltages up to 20 kV and pulses up to 40 kV. High voltage probe was installed between the coil and the spark plug and the voltage traces were captured by the digital oscilloscope.



Figure 3: The profile projection of the spark plug electrode

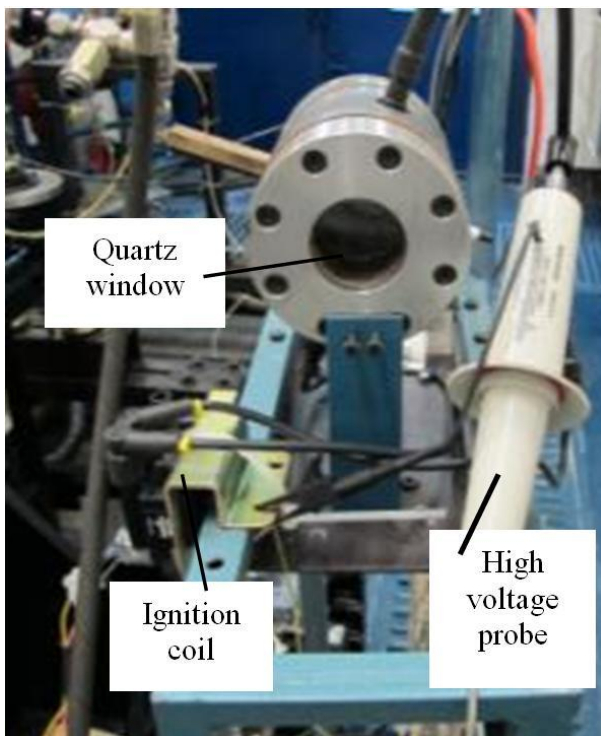


Figure 4: The spark plug test rig and its equipments

### 3) Results and discussion

Results of measurements showed that the pattern of the electrode erosion and the gap growth of a set of spark plugs in various cylinders of the engine are not same. The temperature difference in various

cylinders (cylinders 2 and 3 are hotter) and the direction of the mixture flow through the electrodes could create such a difference. The gap size of a set of spark plugs that was used 220 hours in the endurance test is compared to the primary gap size in Figure 5. The visual investigation of pictures provided by the profile projection showed that electrode sharp edges were removed and the electrode shape rounded, gradually. Moreover, the length, the diameter and the thickness of electrodes reduced and consequently the gap has been widened. As shown in Figure 6, the electrode erosion and the gap growth after 80 hours is not considerable but after 220 hours, in addition to the gap growth, electrode shapes were changed to the rounded shapes (Figure 7).

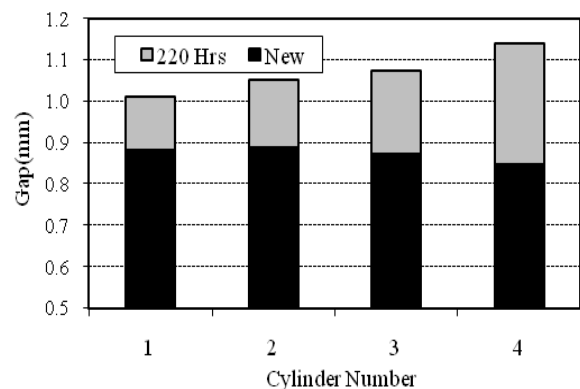


Figure 5: The spark plug gap in various cylinders after 220 hours endurance test

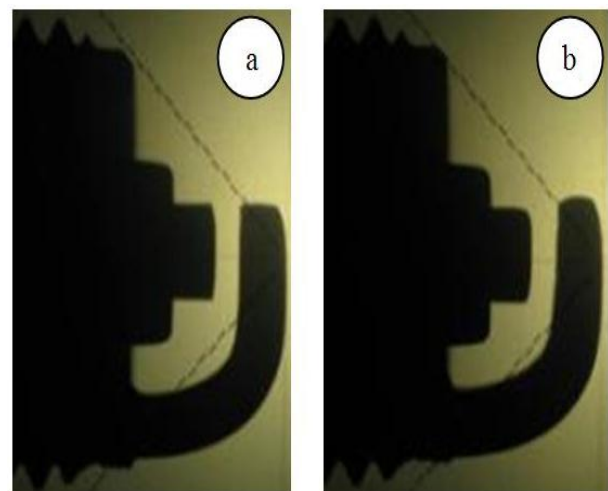


Figure 6: The comparison of the electrodes shape, including (a) a new plug and (b) after 80 hours endurance test

The gap growth versus the running time is shown in Figure 8. As the running time increased, the electrode erosion and the gap size increased as well. For examples, the gap growth after 200 hours is 2 times greater than 80 hours. Whereas, the gap growth after 280 hours was 0.22 mm and it is 4.4 times greater than 80 hours. The trend of the gap

growth is another important issue that should be considered. The gap increased exponentially until 220 hours, but the trend changed after this point. The lifetime expiration of the spark plug could be a reason of this behavior. Indeed a possibility is that until 200 hours, the spark plug has a proper function and the spark occurs between electrodes, but while the running time exceeds from 200 hours, the spark plug performance reduces and the spark occurs in another path which leads to the change of the erosion pattern. This hypothesis could be tested in the spark plug test rig.

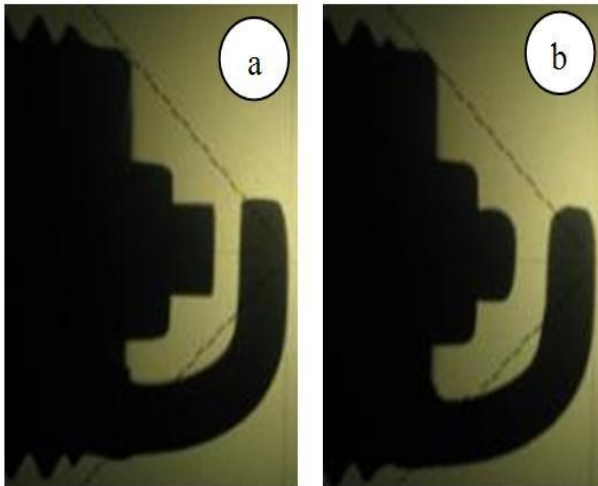


Figure 7: The comparison of the electrodes shape, including (a) a new plug and (b) after 220 hours endurance test

The gap growth rate versus the running time is shown in Figure 9. The investigation of this graph indicates that the gap growth rate is not ascending. As a result, it did not increase by increasing the running time from 80 to 200 hours. Moreover, the gap growth rate after 220 hours was 0.9  $\mu\text{m/hr}$  which decreased to 0.71  $\mu\text{m/hr}$  after 280 hours. This trend could be explained in this way: electrodes in the new spark plug have sharp edges which change to rounded shapes during the engine running time. While edges are sharp, the mixture flow and the flame growth intensify the electrode erosion, but after rounding of edges, the erosion rate decreases. The study of the erosion in any of electrodes justifies the decrease of the erosion rate with the increase in the running time. For examples, the erosion rate of the central electrode is shown by the decrease of the electrode diameter in Figure 10. The diameter reduction has its maximum rate in 80 hours and this rate decreased in higher running times. Thus, the erosion rate after 200 hours is 2.3 times lower than that value in 80 hours.

It should be noted that error bars in Figures 8, 9 and 10 indicate maximum and minimum measured values.

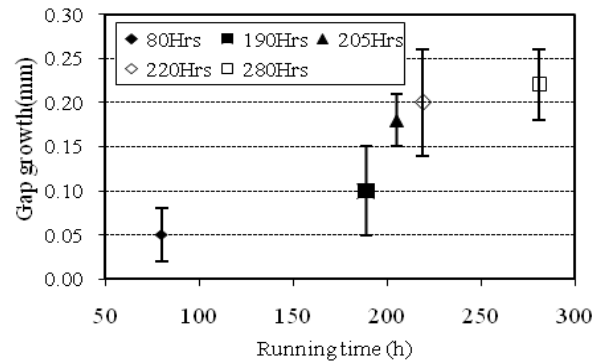


Figure 8: The gap growth versus the running time

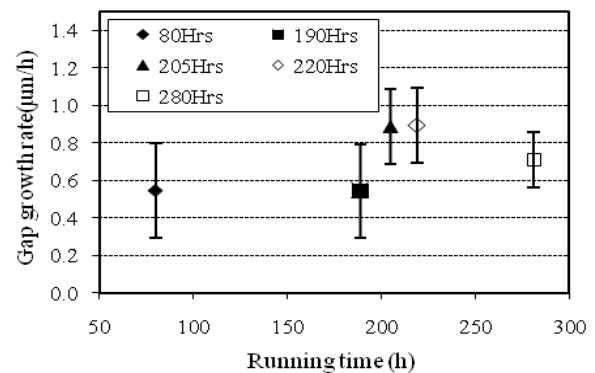


Figure 9: The gap growth rate versus the running time

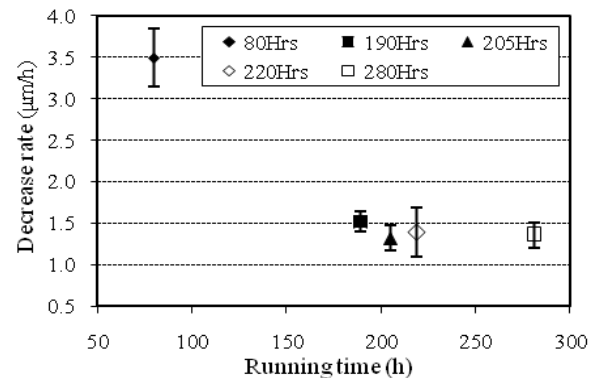


Figure 10: The decrease rate of the diameter of the central electrode after the durability test

The maximum supply voltage of the coil was measured to determine the limitation of the ignition system in the supply of the required voltage which the maximum supply voltage was 24 kV. Next, the required voltage of the new spark plug was measured in various pressures and the sparking quality was investigated to determine a proper pressure for testing of used plugs. The required voltage of new spark plugs versus the chamber pressure is shown in Figure 11. The voltage rises by the increase of the pressure. While the pressure increases from 1 to 9 bar, the required voltage rises more than 2 times. The required voltage in 7 bar is 19 kV which is 5 kV lower than the maximum supply voltage. It means that the required voltage in 7 bar reaches to the maximum allowable range and

pressurizing more than 7 bar reduces the voltage reserve.

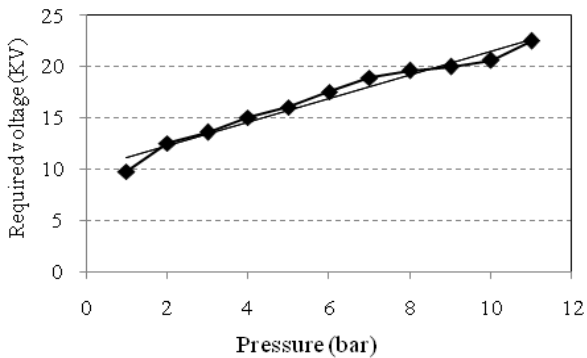


Figure 11: The required voltage of the new spark plug in various pressures

While the voltage reserve has acceptable values (greater than 5 kV), the required voltage increases 1.5 kV per 1 bar increase of the pressure. The required voltage of the plug that has 0.9 mm gap for sparking in nitrogen could be calculated from Equation 2. Unlike the Paschen law, the gap size has been considered and this expression could be used in the extended range of pressures. Equation 2 is obtained by the evaluation of the original spark plug that can be developed for the rested engine. Thus, it could be a proper relation to evaluate the new type of spark plugs (conventional J-gap plugs) which are a candidate for the tested engine.

$$V = 1.156P + 9.97 \tag{2}$$

In Equation 2,  $V$  is the required voltage in kV and  $P$  is the chamber pressure in bar. The gap size of used spark plugs was increased and electrodes have been rounded off, consequently. The required voltage for these spark plugs was greater than new plugs. Therefore, the chamber pressurized only 5 bar to have an adequate voltage reserve for all used spark plugs. The required voltage of used plugs versus the running time is shown in Figure 12.

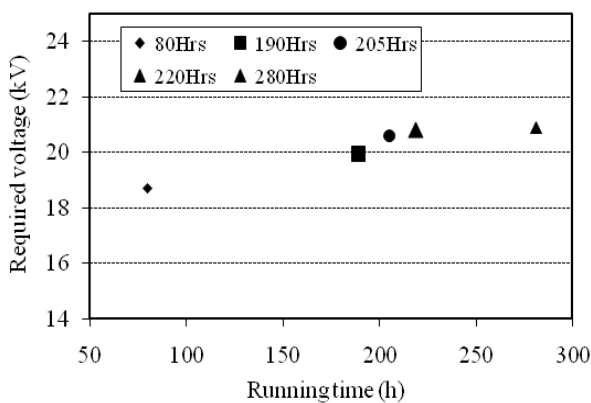


Figure 12: The required voltage of used spark plugs (at 5 bar)

The required voltage as a function of the gap size is shown in Figure 13. If the gap growth increased 20%, the expected required voltage increases 11%. The required voltage for used spark plugs can estimate by Equation 3.

$$V = 9d + 11.03 \tag{3}$$

In which,  $V$  is the required voltage in kV and  $d$  is the gap in mm.

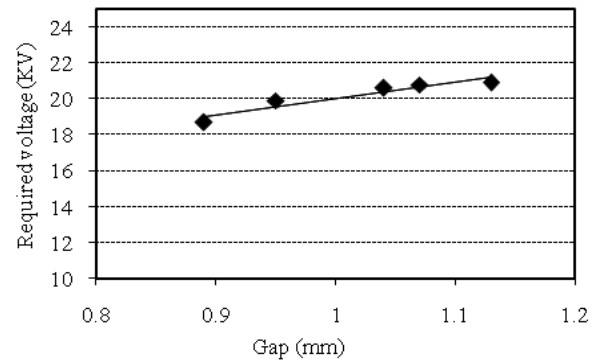


Figure 13: The effect of the gap growth on the required voltage (at 5 bar)

These relations are extracted considering the gap width and the required voltage and the supply voltage of the coil after durability tests. Thus, regardless to the spark plug heat range, the electrode erosion and the durability cycle are reliable for conventional J-gap spark plugs that will use in this engine.

An important point that should be considered is the effect of used plugs - regardless of the gap growth - on the required voltage. Based on the results, the required voltage at 5 bar for used spark plugs (after 80 hours) which have 0.89 mm gap is 18.7 kV. Whereas the required voltage of new plugs (with 0.88 mm gap size) is only 16 kV. Such results indicate that used plugs could increase the required voltage and affect spark properties. Deposits and oxide layers which have electrical insulator properties are a cause of this behavior [7].

Used plugs could affect on the spark quality. Thus, the spark path was studied visually in the spark plug test rig. In this rating process, the spark path between electrodes is considered as a base for the evaluation of the sparking quality. Sparks that occur between central and ground electrodes, are a proper spark and if the spark have another path such as side sparking (between the central electrode and housing) is improper. Side sparking could lead to the increase of the cyclic variation of the indicated mean effective pressure (COV) [19]. A proper spark and various types of improper sparks are shown in Figure 14.

The investigation of the sparking quality shows that plugs with 80 hours running time have proper sparking and sparks occur between ground and

central electrodes. Also, after 200 hours, the sparking quality is good. On the other hand, the side spark occurs in plugs with 220 and 280 hours running time. Thus, as the running time increases, the sparking quality decreases. The required voltage of these plugs is 20.8 and 20.9, respectively. These values are lower than the maximum supply voltage, therefore, it is expected that the sparking quality have not declined. But the resistance of the insulator has been decreased by the carbon deposit and as a result, the path of the electrical discharge has been changed.

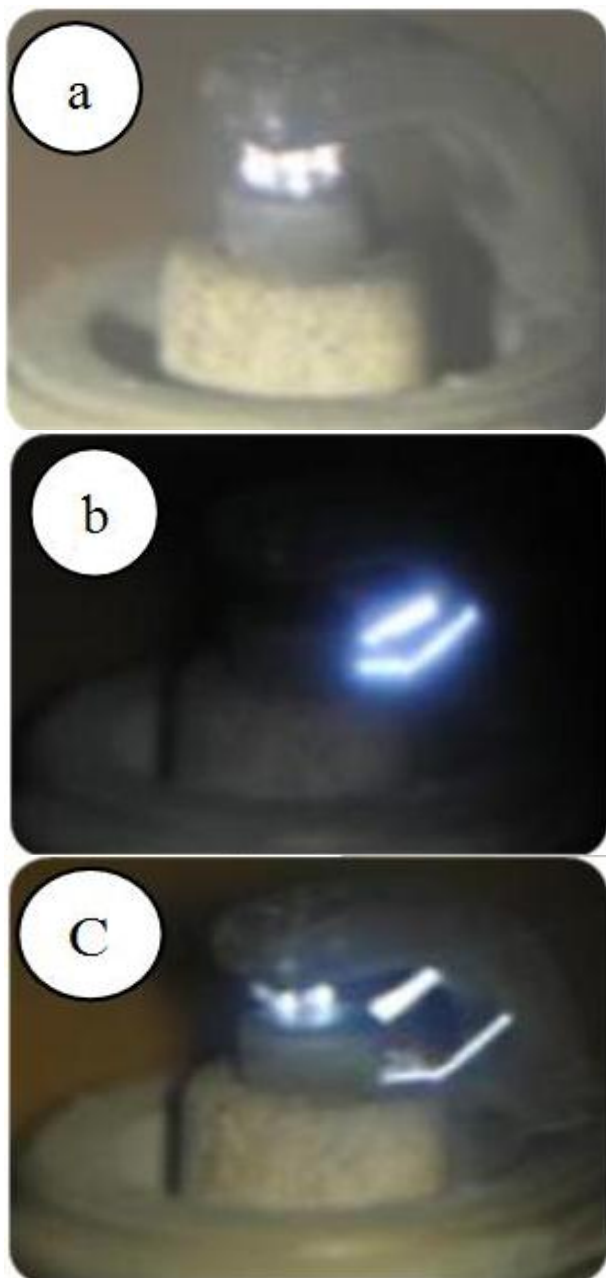


Figure 14: Spark types including (a) a proper spark, (b) a side spark and (c) a side spark combined with the spark in the gap

#### 4) Conclusion

According to results of this study, the gap increases with the running time, but the electrode erosion rate and the gap growth rate have not an ascending trend. While spark plugs are new and electrodes have sharp edges, the erosion rate has higher values, but the erosion rate decreases, gradually. For examples, the decrease rate of the diameter of the central electrode after 200 hours is 2.3 times lower than plugs with 80 hours running time.

The usage of used spark plugs could increase the required voltage. The gap growth is one of the main reasons that increases the required voltage. As a result, 20% growth of the gap led to 11% rise of the required voltage. The comparison between new and used plugs (with 80 hours running time) shows that despite having the same gap size, the required voltage of used plugs is 2.7 kV higher than new plugs. Electrical insulator deposits could be a cause of this difference. Deposits also affect on the spark quality and the spark path changes from the gap to side sparking between the central electrode and housing.

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#### Nomenclature

$d$	Spark plug gap distance
$N_2$	Nitrogen
$P$	Pressure
$V$	Required voltage
CNG	Compressed Natural Gas
COV	Coefficient of Variation in indicated mean effective pressure

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سعید جوان<sup>۱\*</sup>، سید وحید حسینی<sup>۲</sup>، سید شهاب‌الدین علویون<sup>۳</sup>، فتح‌اله امی<sup>۴</sup>

<sup>۱</sup>شرکت تحقیق، طراحی و تولید موتور ایران خودرو (اییکو)، تهران، ایران، [s.javan@ip-co.com](mailto:s.javan@ip-co.com)

<sup>۲</sup>شرکت تحقیق، طراحی و تولید موتور ایران خودرو (اییکو)، تهران، ایران، [v.hosseini@ip-co.com](mailto:v.hosseini@ip-co.com)

<sup>۳</sup>شرکت تحقیق، طراحی و تولید موتور ایران خودرو (اییکو)، تهران، ایران، [sh.alaviyouon@ip-co.com](mailto:sh.alaviyouon@ip-co.com)

<sup>۴</sup>دانشگاه تربیت مدرس، تهران، ایران، [fommi@modares.ac.ir](mailto:fommi@modares.ac.ir)

\*نویسنده مسئول، شماره تماس: ۰۹۱۲۵۶۱۱۶۴۷

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رفتگی الکترودها

ولتاژ مورد نیاز جرقه

در این مقاله، میزان رفتگی الکترودها و افزایش دهانه شمع‌ها، بعد از آزمون‌های دوام اندازه‌گیری شد. سپس، ولتاژ مورد نیاز جرقه و کیفیت جرقه‌زنی تمامی شمع‌ها در سامانه آزمون قطعه‌ای شمع، بررسی گردید. بر اساس اندازه‌گیری‌ها، با افزایش ساعت کارکرد، دهانه شمع‌ها افزایش می‌یابد؛ بطوری‌که میزان افزایش دهانه، بعد از ۱۸۹ و ۲۸۱ ساعت کارکرد، به ترتیب ۲ و ۴٫۴ برابر میزان افزایش دهانه برای شمع‌هایی با ۸۰ ساعت کارکرد می‌باشد. اندازه‌گیری ولتاژ مورد نیاز جرقه نشان می‌دهد که با افزایش فشار، ولتاژ مورد نیاز جرقه افزایش پیدا می‌کند؛ بطوری‌که در هنگام استفاده از شمع‌های نو با افزایش فشار از ۱ به ۹ بار، ولتاژ مورد نیاز جرقه ۲ برابر افزایش پیدا می‌کند. بر اساس نتایج آزمون‌ها، افزایش ساعت کارکرد شمع منجر به افزایش رفتگی الکترودها و در نتیجه افزایش ولتاژ مورد نیاز شده است. این پدیده، تاثیر منفی بر کیفیت جرقه‌زنی داشته است. بررسی نتایج نشان می‌دهد که با افزایش ۲۰ درصدی دهانه شمع، ولتاژ مورد نیاز در فشار ۵ بار بیش از ۱۱ درصد افزایش یافته است. مقایسه نتایج اندازه‌گیری رفتگی الکترودها و ولتاژ بین شمع‌های نو و کارکرده نشان می‌دهد که علاوه بر افزایش دهانه شمع، رسوبات سطح الکترودها در شمع‌های کارکرده می‌تواند سبب افزایش ولتاژ مورد نیاز جرقه شود.

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