An Experimental Investigation of Spark Plug Temperature in Bi-fuel Engine and Its Effect on Electrode Erosion

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Abstract

Temperature is one of the effective parameters in erosion of spark plug electrodes. In this research, temperature of spark plug was measured in engine's different operation conditions with two types of fuels: compressed natural gas and gasoline. Test results showed that, temperature of center electrode is lower than ground electrode and maximum difference between them is 110ºC that occurs at 2500 rpm and full load conditions. Maximum temperature of spark plug occurs with CNG under full load conditions and 6380 rpm. In these conditions, ground electrode's temperature reaches to 960ºC which is very prone to pre-ignition. On the other hand, center electrode's temperature is 195ºC higher than the same condition with gasoline as a fuel which cause more electrode erosion rate. This temperature rise lead to cold type spark plug selection because of its better heat transfer. Spark plug erosion was studied after endurance tests with CNG as a fuel. Electrodes have non uniform wear patterns and consequently gap growth is not uniform. The average gap growth for two sets of spark plugs after two similar 200 hr endurance tests is 49.6%.

Keywords: *Bi-fuel engine, spark plug, Temperature, Electrode erosion.*

1. INTRODUCTION

Considering limit sources of crude oil and stringent emission regulations, alternative fuels are desirable for diesel and gasoline engines. CNG is a clean fuel with wide sources and other special properties which could use as an alternative fuel for gasoline and diesel [1-3]. Bi-fuel engine which uses CNG and gasoline is one of the technologies that developed for this purpose. In design of bi-fuel engine, the features of both fuels should be considered to satisfy three important expectations: lower fuel consumption, lower emission and proper function of engine. The combustion of air/fuel mixture is main task of spark plug in spark ignition engines. Spark plug should produce more than thousand sparks per minute in combustion chamber under high pressures and temperatures. Adverse function of this part of engine leads to reduce engine performance, rise of emission and could damage other engine parts. Synchronically with developments in design of internal combustion engines, compression ratio of recent engines has been increased to reach higher thermal efficiency. However, modifications to accordance with emission regulations and lower fuel consumption are cause of intensify thermal loads on spark plugs [4]. Spark plug is subjected to combustion thermal loads and should have proper heat transfer. The main part of heat has been dissipated into cylinder head and coolant by spark plug thread [5]. Working heat range of spark plugs is shown in figure 1. Spark plugs are designed to work within the ideal heat range of 400ºC to 850ºC [6-8]. If plug tip temperature exceed from allowable range, not only erosion behavior of electrodes may risen, but also air-fuel

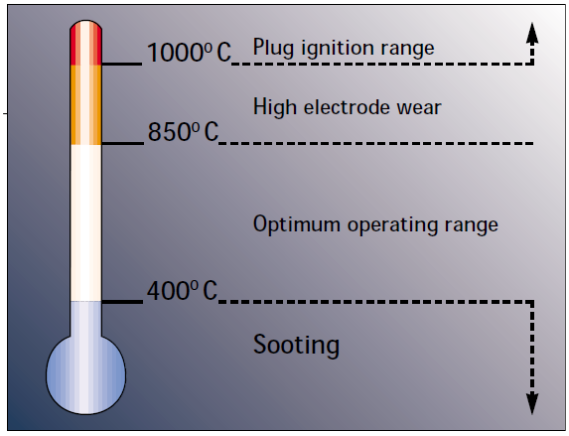

Fig. 1. spark plug temperature [8]

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mixture in the combustion chamber tends to pre-ignition. On the other hand, if the temperature is less than about 400°C, the insulator tip and electrodes tends to foul with carbon and oil deposits, which can cause misfires [5, 7].

Spark plug temperature has intensive dependence to insulator and electrodes length. Moreover these parameters, electrode materials and design of electrode tip could affect on heat transfer [9, 10]. Considering these factors, spark plugs categorize in two main groups that are called hot and cold type.

Engine operation with CNG (compressed natural gas) fuel increases required voltage and leads to higher material removal from electrodes [11]. Poor combustion quality is result of electrode erosion and low spark quality. When spark plug gap increases due to electrode erosion, strength of electric filed is increased. So this can lead spark plug to side sparking. In this phenomenon, resistance of insulator reduces by carbon deposit and spark occurs between insulator nose and spark plug housing [6]. Correct spark path at spark plug gap and side spark path are shown in figure 2. Sparking and oxidation are two main mechanisms of erosion in spark plugs. Sparking wear is consequence of ion bombardment that is produced by ionization of air-fuel mixture between electrodes. Oxidation wear occurs in high temperatures that oxygen permeates in the electrode surface and creates chemical bonds. These components weaken surface of electrodes and gradually flake off oxide layer from electrode surface. Then new oxide layer has been generated on the surface and flake off again. This repeated process is cause of gap growth. Electrode temperature rises locally by voltage discharge, and then electrode surface melts and dissipates. Dispersion of material from electrodes tip will increase electrode erosion. Generally, sparking wear arises in center electrode and oxidation wear is important in ground electrode [12-14].

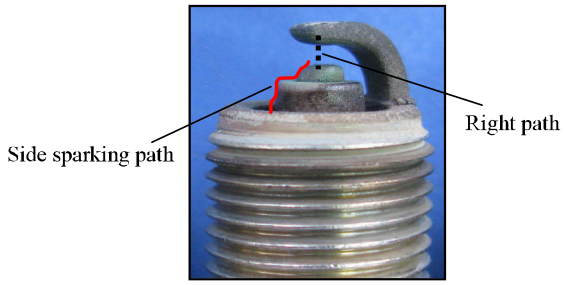

Fig. 2. Right sparks and side sparking path

Electrode erosion has great dependence to temperature so that, electrode erosion accelerates in high temperatures. Particularly ground electrode has critical conditions, since it has deeper protrusion in combustion chamber and suffers higher temperatures [12]. The temperature of electrodes depends on some parameters such as sparking advance angle, engine speed, engine load, fuel type, compression pressure, and air fuel ratio [5, 15].

In devolvement of bi-fuel engines it is necessary to have studies about electrode temperature to select or design proper spark plug for certain engine. In this research, temperature of spark plug electrodes is measured in gasoline-CNG bi-fuel engine at different operation conditions of engine and effect of fuel type on spark plug temperature is investigated.

2. EXPERIMENTAL METHOD

2. 1. Engine and Experimental Equipments

A bi-fuel, natural aspirated spark ignition engine is used in experiments. The fuel system is multi point port injection and other technical specifications of this engine have been presented in table 1.

Different temperature and pressure sensors were

Table 1. Engine technical specifications

Cylinders	4
Arrangement	Inline
Bore	78.6 mm
Stroke	85 mm
Displacement Volume	1649 cm^3
Compression Ratio	11.05
Maximum Power	84 kW
Maximum Torque	149 N.m
Idle Speed	750 rpm
Maximum Speed	6400 rpm

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installed on the engine to trace engine function. For example K type thermocouples are used for measuring temperature of exhaust gases at exhaust manifold outlet and j type thermocouples have been installed at intake manifold. These thermocouples can measure temperature at range of -200 ºC to 1270 ºC with ±1% accuracy. Data recording rate during experiments was 1 Hz.

2. 2. Preparation for Measuring Electrode Temperature

Conventional J type spark plugs are used in temperature test. Main dimensions of spark plug such as Gap, diameter and length electrodes (Fig.3) are presented in table 2. These dimensions are measured with Mitutoyo pj-2500 profile projection.

For measuring temperature of center electrode, a narrow hole is created from connection nut to end of center electrode, and then K type thermocouple with 0.8 mm diameter is fixed into the bore. This spark plug and is shown in figure 4. Thermocouple's tip position is 2 mm above the end of center electrode. Figure 5.a shows another spark plug which is prepared for measuring temperature of ground electrode. This spark plug is equipped with K thermocouple too. Thermocouple has joined to ground electrode with a brazing metal joining process. Brazing produces a clean joint without the need for secondary finishing and also produces less thermal distortion than welding due to the uniform heating of a brazed piece. Before starting measurements the proper function of prepared spark plugs (spark plug and thermocouple) is validated in calibration furnace (figure 5.b). Also, measurements are repeated to ensure uniformity of results.

Table 2. Dimensions of spark plug which is used for temperature test

Model	J type Ni base electrodes
Gap	0.75 mm
Center electrode diameter	2.97 mm
Center electrode length	1.45 mm
Ground electrode thickness	1.24 mm

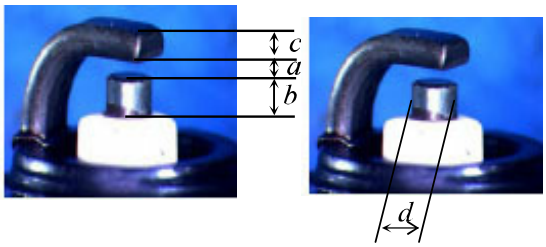

Fig. 3. a) gap, b) length of center electrode, c) thickness of ground electrode, d) diameter of center electrode

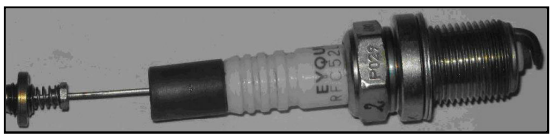

Fig. 4. Prepared spark plug for measurement of center electrode temperature

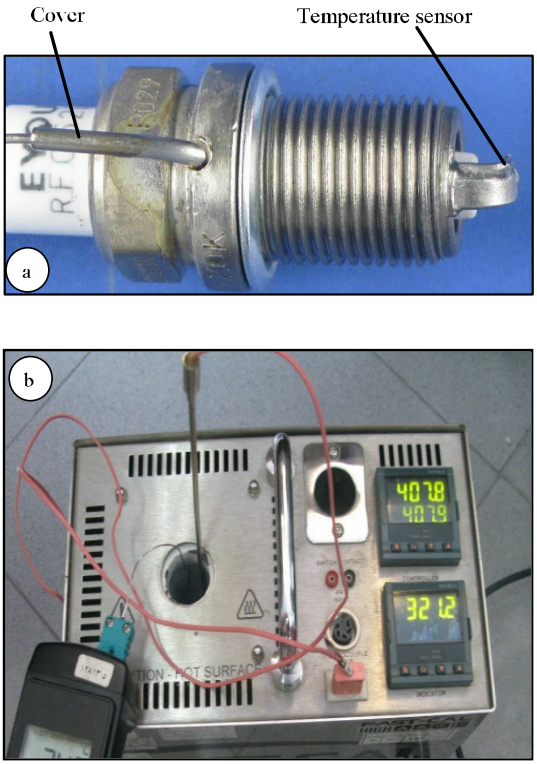

Fig. 5. a) prepared spark plug for measurement of ground electrode temperature b) Validation of measurement spark plug by electrical furnace

2. 3. Experimental Method

Spark plug temperature is measured for two types of fuels: CNG and gasoline. This test is performed in

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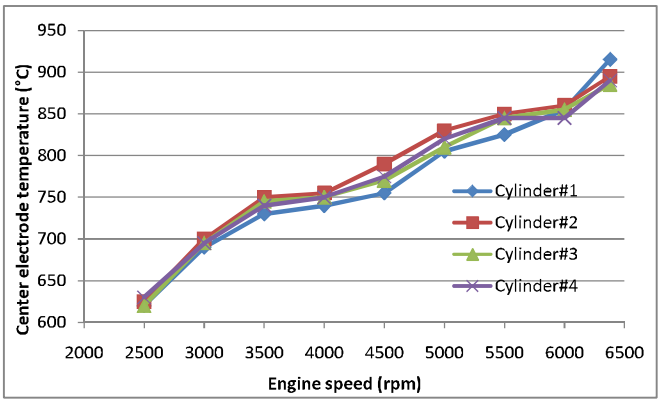

Fig. 6. Average temperature of center electrode in full load conditions

different engine operation conditions such as cold start, idle speed, part load and full load. First, to identify the hottest cylinder and hottest operating point, the temperature of center electrode is measured in all cylinders with using CNG. Cylinder #2 has the highest temperature in most operating points and the average temperature of this cylinder is higher than others. Whereas temperature of cylinder 1 is lower than cylinder 2 in most working points. So cylinder 2 is hotter than other cylinders and other measurements have been performed in this cylinder. Results of center electrode temperature are shown in figure 6. The variation of temperature in various cylinders is due to heat transfer and coolant effect. Cylinders 2 and 3 are mounted between other cylinders and are subjected to heat transfer of cylinder 1 and 4. Indeed both sides of these cylinders are subjected to the hot solid. Whereas cylinders 1 and 4 could reject heat to ambient from one side and are cooler cylinders.

In addition, two types of cold starting tests were conducted: first, start at ambient temperature and operation under idle conditions. Second is started and gone immediately to part load conditions with 2 bars BMEP and 2000 rpm. In full load conditions measurements are started at 1000 rpm and for each step, engine speed is increased 500 rpm until maximum engine speed at 6380 rpm.

3. RESULTS AND DISCUSSIONS

3. 1. Temperature of Center and Ground Electrodes

By increasing engine load and speed, electrode temperature increases and maximum temperature occurs in full load conditions. Figure 7 shows comparison between temperature of center and ground

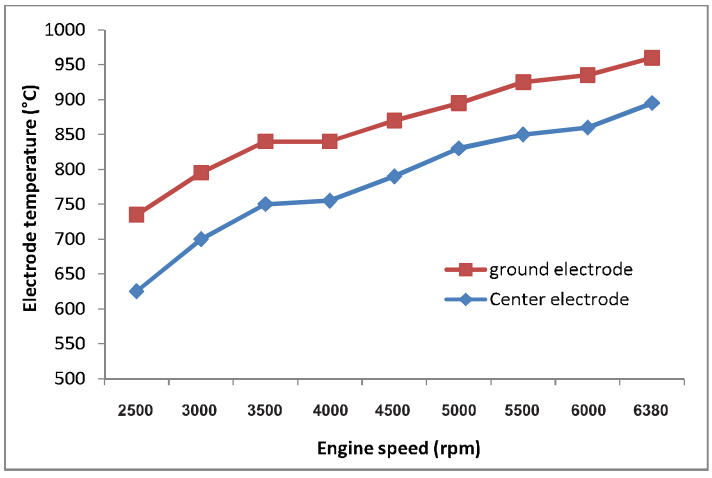

Fig. 7. Temperature of ground and center electrodes under full load conditions.

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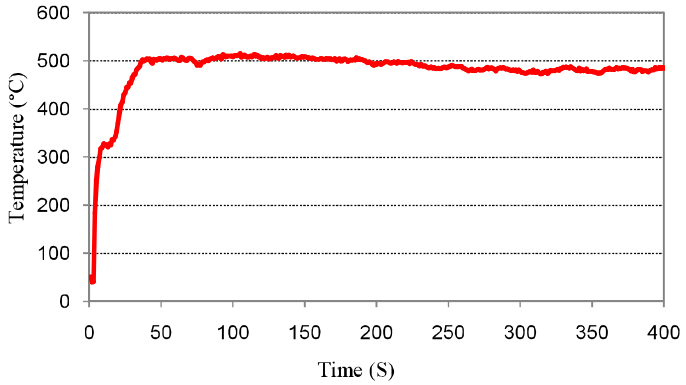

Fig. 8. Variations of ground electrode's temperature from start till 2000 rpm and 2 bars using CNG as a fuel.

electrodes in full load conditions. In all of operating points the ground electrode is hotter than center electrode, since ground electrode's has deeper protrusion in the combustion chamber, which causes to absorb more heat form combustion products. Center electrode's temperature is 110 ºC lowers than ground electrode at engine speed 2500 rpm. By increasing engine speed, the difference between temperature of electrodes declines until 65ºC at 6380 rpm.

3. 2. Temperature of Ground Electrode in Different Engine Operation Conditions

3. 2. 1. Cold Start

Engine started at ambient temperature (22ºC) and was gone to operation point with 2000 rpm and 2 bars BMEP within 5 seconds ramp. Temperature of ground electrode versus time is shown in figure 8. Electrode temperature reaches to steady state after 50 seconds. Average temperature of ground electrode is 490 ºC for CNG and this quantity is 485ºC for gasoline.

3. 2. 2. Idle Speed

Figure 9 shows variations of ground temperature in idle speed from engine starting until temperature reaches steady state. Although electrode temperature reaches steady state conditions in the same time for CNG and gasoline, temperature of ground electrode with CNG is higher than gasoline. Average temperature of ground electrode for idle speed while engine operates with CNG and gasoline is 310ºC and 300ºC respectively. Carbon deposits that have been accumulated on the insulator tip burn at 400ºC to 450ºC [6-8] but average temperature of ground

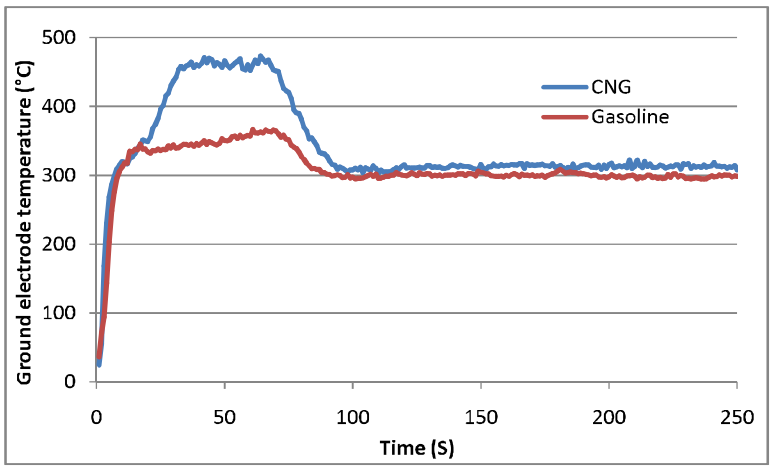

Fig. 9. Ground electrode temperature in idle speed

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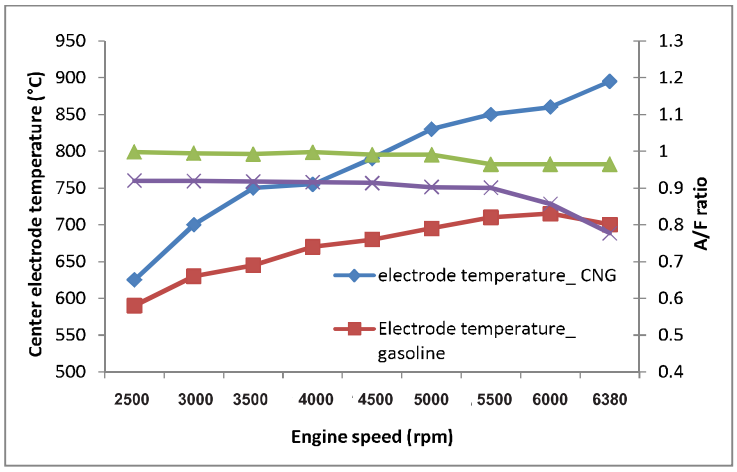

Fig. 10. Comparision of center electrode temperature and A/F ratio between CNG and gasoline in full load conditions.

electrode for both CNG and gasoline is lower than this range. However engine operation at idle conditions will result in increase of carbon deposit on spark plug insulator.

3. 3. Effect of Fuel Type in Electrode Temperature

Maximum temperature of electrodes occurs in full load conditions. While engine operates with CNG, electrode temperature rises as the engine speed increases and finally reaches its maximum value at 6380 rpm. But electrode temperature has different trend in gasoline mode and it reaches maximum value at 6000 rpm and then decreases. Center electrode temperature versus engine speed is shown in figure 10.

In comparison to gasoline, combustion of CNG has lower flame speed. Hence average temperature of gases in combustion of CNG mixture is higher than gasoline mixture. Therefore, spark plug that is exposed to combustion of CNG is hotter.

Investigation of electrode temperature while engine operates with gasoline shows that ascending rate of electrode temperature decreases between 5500 and 6000 rpm. Also, by increasing speed, electrode temperature decreases after 6000 rpm. Air/fuel ratio is one of parameters that affects on electrode temperature. So that, electrode has its maximum temperature around 13:1 A/F and richer mixtures could decrease temperature [5, 16]. Variations of air/fuel ratio (λ) for gasoline and CNG mixtures

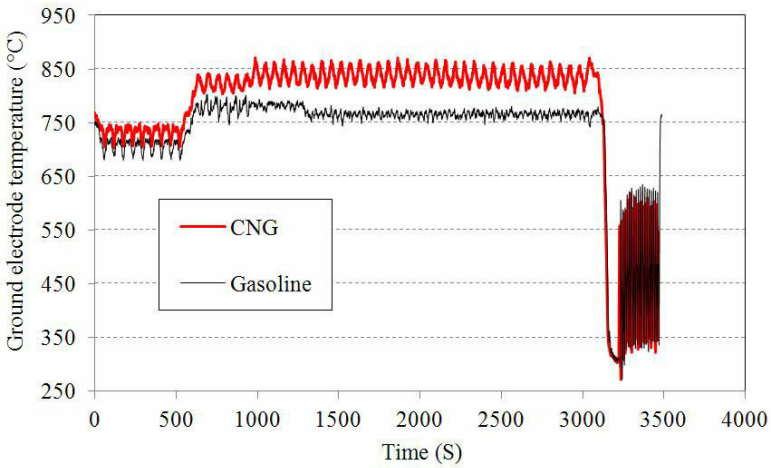

Fig. 11. Variations of ground electrode temperature during a cycle of durability test.

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under full load conditions is shown in figure 10. For gasoline mixture maximum value of λ is occurred at 1500 rpm and after this point air /fuel ratio declines gradually. But A/F is higher than 13:1 till 5500 rpm and it has more declines after this point. So that, mixture become richer than 13:1 and consequently electrode temperature declines. Variations of for CNG mixture is very low and has not considerable effect on electrode temperature.

In order to investigate about effects of fuel type on temperature of electrode, temperature of ground electrode is measured during a cycle of durabilty test. During this test engine operates in various conditions transiently. Results show that avearge temperature of electrode which is operated on CNG and gasoline is 780ºC and 730ºC respectively. Actual temperature variations during the cycle are shown in figure 11.

3. 4. Investigation of Electrode Erosion

Figure 12 shows electrode erosion rate versus temperature for materails that typically used in spark plugs. Electrodes temperature lower than 500°C have no significant effect on electrode erosion. If electorde temperature is rised more than 500ºC, it has accelarated erosion with logarithmic behavior.

accelerates electrode erosion. Spark plugs that are used in this research have nickel based electrodes. Considering Ni erosion rate, raising averaged temperature from 730°C on gasoline mode to 750°C on CNG mode could conclude to excessive electrode erosion.

Therefore, durability test have been conducted with CNG. Measurment of electrodes shows same wear pattern in two sets of spark plugs from two equal durability tests. Figure 13 shows spark plug befor and after of durability test. Length and diameter of center electrode are decreased and spark plug gap is increased. Electrodes have non uniform wear pattern as shown in figures 13 and 14, so growth of spark plug gap is not uniform too. Dashed lines in figure 14 are representative of electrode dimensions befor durability test. Comparision between electrode dimentions represent intensive electrodes erosion. Table 3 represents dimensions of spark plug before and after durabilty test.

Maximum and minimum gap growth for two sets of spark plugs with about 200 hours runnuing time in durability test cycles are 90% and 40% respectively.

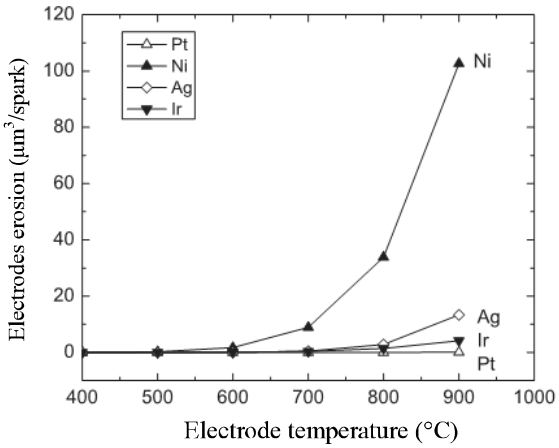

Fig. 12. Electrode erosion respect to temperature [14].

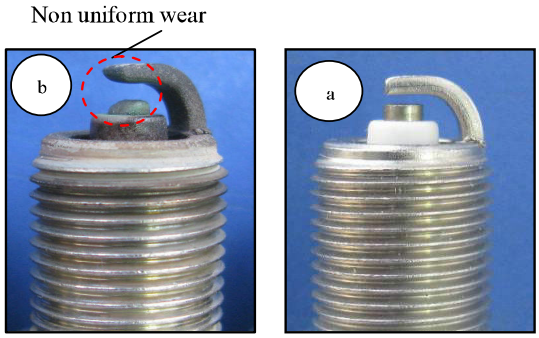

Fig. 13. Appearance of spark plugs a) before durability test b) after durability test.

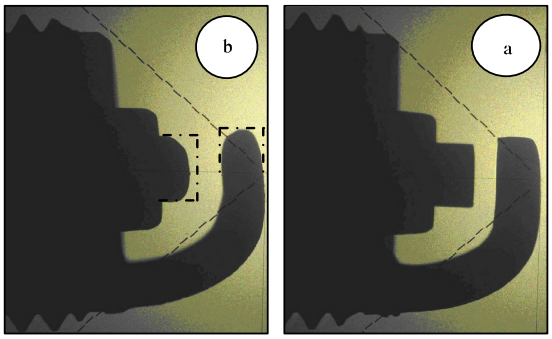

Fig. 14. Study of electrode erosion under profile projection a) before durability test b) after durability test.

Required voltage increases with gap growth so that if it exceed from certain limit, the ignition coil could not support required voltage for proper sparking [16-18]. Hence, more elctrode erosion which causes by CNG

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Table 3. dimentions of spark plug after about 200 houre running in off road durabilty test.

Gap (mm)			Center elctrode's diameter (mm)		Center electrode's length (mm)			Ground electrode's thickness (mm)	
Initial	Min	Max	Initial	Min	Initial	Max	Min	Initial	Min
0.75	1.19	1.69	2.97	2.40	1.45	0.93	1.1	1.25	1.16

fuel could lead to misfires and more limtations for spark plug life time.

4. CONCLUSIONS

Experimental results show that temperature of center electrode is lower than ground electrode and maximum difference between temperatures of these electrodes is 110°C which occurs at 2500 rpm under full load conditions. This difference could result in higher oxidation erosion of ground electrode and it is necessary for ground electrode to have more oxidation resistance rather than center electrode. There is not considerable difference between temperature of electrodes with gasoline and CNG for engine operation at idle or low speed part load condition. Temperature reaches to steady state conditions after 50 second while engine started in ambient temperature and ramped immediately to working point; 2000 rpm and BMEP= 2 bar. In these conditions, ground electrode's temperature in CNG mode is 5°C hotter than gasoline. This difference reaches 10°C at idle speed which is inconsiderable. While engine operates at idle speed and low speed part load conditions, the electrode temperature is lower than safe range and this could result to carbon fouling and adverse effect in engine acceleration.

Maximum temperature of electrodes occurs when engine operates with CNG at 6380 rpm and full load condition. In these conditions temperature of ground electrode reaches 960°C that is 350°C more than temperature at idle speed. Investigation about effects of fuel type on temperature shows that, temperature of electrodes while engine operates with CNG are higher than gasoline. For one cycle of durability test, average temperature of ground electrode with CNG is 50°C more than gasoline. Also, temperature of center electrode with CNG is 195 °C higher than gasoline at 6380 rpm and full load conditions. Rise of electrode temperature under full load condition could result to pre-ignition at higher engine speeds. Also, this temperature rise accelerates electrode erosion rate in nickel base electrodes and has intensive impact on sprk plug life time which demonstrate necessity of using cold type spark plug with high resistance to oxidation in CNG-gasoline bi-fuel engines. Nickel based electrode with special addetives such as Si-Y-Ti also, Platinum electrodes have high oxidation resistance which could replace with conventional nickel spark plugs in bi-fuel engines.

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