Proceedings of the 11th World Congress on Electrical Engineering and Computer Systems and Sciences (EECSS'25)
Paris, France - August, 2025
Paper No. EEE 121
DOI: 10.11159/eee25.121

Characteristics of Discharge Phenomena on Novel Ceramic-Pipe Covered Cathode

Isak L. SHAWAPALA[1], Akira SUGAWARA[1], Kaho HAYAKAWA[1]
[1]Graduate School of Science and Technology, Niigata University
8050 Ikarashi-2, Niigata City, 950-2181, Japan
f23l001a@mail.cc.niigata-u.ac.jp; akira@eng.niigata-u.ac.jp; f25c040b@mail.cc.niigata-u.ac.jp

Abstract - Electric discharge phenomena are crucial in various technological applications, from power systems and automotive to plasma generation. The automotive industry has always been at the forefront of technological advancements, and the evolution of spark plugs is no exception. This examines innovation in spark plug technology by integrating the creepage discharge method to enhance ignition sparks and minimize variation in ignition energy discharge. This article compares a ceramic rod cathode electrode (CRC) with a ceramic pipe-covered cathode (CCC). The experiment involves changing the positions of the ceramic pipes to examine the voltage at which the spark is discharged and then computing the variations in the sparks' energy. It considered two patterns, the CRC and CCC, as the positions of the ceramic pipe on the cathode. The results show an intense spark discharge for CCC, with lower spark energy and less variation in spark energy compared to CRC. In conclusion, this provides a glimpse into the intriguing realm of electric discharge creation through the creepage discharge method, which reduces discharge voltage variation and produces more vital sparks for ignition. Incorporating this novel technique opens up possibilities for enhancing spark plugs. The findings contribute to understanding the fundamental processes involved and offer opportunities for advancements in plasma discharge technology domains.

Keywords: spark discharge voltage, creeping discharge, spark discharge energy, ceramic pipe, discharge energy variation, cathode, triple junction

1. Introduction

Spark discharge is a transient discharge characterized by intense flashes and loud sounds. When the voltage exceeds a certain limit, sparks are observed between the electrodes. At the moment of discharge, the cathode and anode are connected by a highly conductive discharge path, resulting in dielectric breakdown (total path failure) [1]. The transient phenomenon that occurs on the way to dielectric breakdown is called a spark discharge [2], [3]. Normally, the phenomenon of spark discharge that occurs in the atmosphere varies depending on the type of applied voltage (DC voltage, AC voltage, pulse voltage, etc.), its polarity, ambient conditions (temperature, humidity, etc.), and the shape and dimensions of the electrodes [4]–[7]. When a spark discharge flows continuously, it becomes a glow discharge or an arc discharge. This type of discharge phenomenon is commonly applied to spark plugs, ozonisers, and electrical discharge machines, among others. For example, in spark plugs, various issues persist, including flashover voltage reduction during spark discharge initiation, electrode life, and ignition delay.

On the other hand, price hikes and higher carbon dioxide emissions have resulted from the restricted ability to supply fossil energy due to limited production capacity, infrastructure, and dwindling fossil fuel resources [8]. Governments have implemented regulations to control harmful emissions and encourage fuel economy [9]. Although progress has been made in the automotive industry to reduce pollutant emissions, catalytic converters still face challenges such as low efficiency, untreated contaminants, and uncatalyzed engines. Therefore, it is best to work upstream of the catalytic converter. Researchers must develop new methods to enhance combustion while consuming less fuel and producing fewer emissions. Higher-pressure combustion and low air/fuel mixes are two solutions for the automotive industry. However, more energy is required to improve combustion quality than is typically provided by a spark plug [5]. The electric discharge generated between the electrodes of a classic spark plug could not ensure fast and complete combustion of the air-hydrocarbon mixture. A clean and efficient thermal engine requires the rapid and complete combustion of the poor air-hydrocarbon mixture, which can be achieved using an improved ignition system [10]. To guarantee ignition, direct spark ignition/electric discharge must be precisely engineered, i.e., with the largest possible volume and heat energy, to transfer maximum energy to the mixture. Direct spark discharge for ignition must be carefully designed to ensure ignition and prevent electrode deterioration and damage to the combustion chamber from pressure spikes [11].

Typically, a conventional spark plug cathode protrudes from the ceramic cover, forming a Ceramic-rod cathode (CRC). This paper proposes a new ignition system configuration designed to achieve efficient discharge. A ceramic pipe is introduced to cover the tip of the rod electrode completely, forming a ceramic-covered cathode (CCC); hence, the triple junction and creepage discharge effect strengthen the spark discharge and improve stability. The CCC discharge energy is compared with the discharge and a cathode not covered by the ceramic pipe. The energy stored in the capacitor is used to evaluate the proposed spark plug energy. Based on these results, we report the discharge characteristics of the dielectric-coated rod electrode and compare them to those of a conventional spark plug.

2. Methodology

This work analyzes the voltage waveforms and the discharged plasma between the electrodes. The gap length between the anode and cathode *d* is kept constant. At the same time, the ceramic pipe is moved to change length *L* as shown in Fig. 1. Length *L* is from the ceramic pipe tip to the tip of the negative electrode, and length *d* is the gap between the two electrodes, as shown in Fig. 1. Two patterns of L (L = -2 mm and L = 2 mm) are examined.

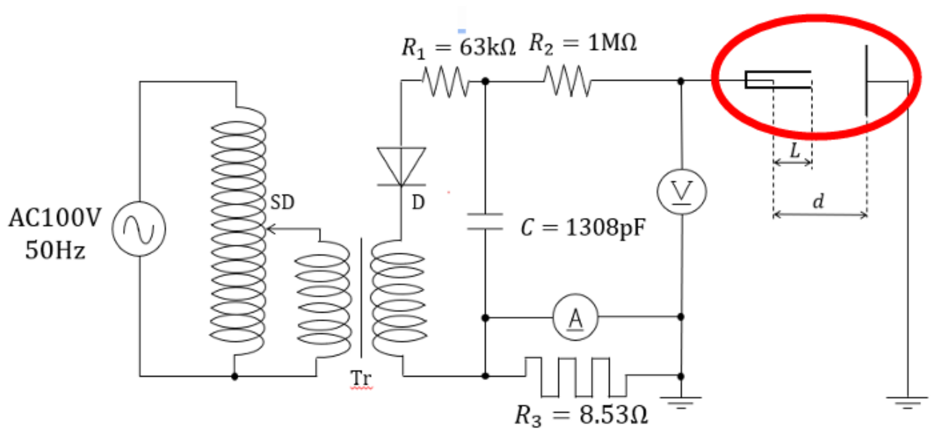
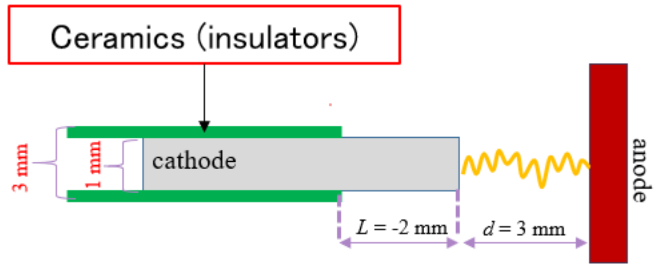


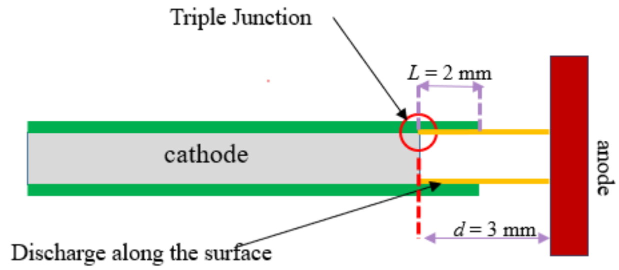
Fig.1 Experimental circuit.

The system consists of an electric spark generator and measurement units. The electric spark generation is composed of a high-voltage power supply (SD and Tr transformers), an energy storage bank (two capacitors (2719 pF and 2522 pF) with a series combined capacitance C of 1308 pF), resistors (R_1, R_2 and R_3), a diode D, a stainless rod-wire (cathode), with the diameter of 1 mm, a copper electrode (anode) with a diameter of 40 mm and 10.15 mm thickness, and a ceramic pipe with diameter of 2 mm. The electrode part is enclosed in a chamber (red circle in Fig. 1). A high voltage of up to 20 kV is applied to the cathode. Furthermore, there are two motors, each driving an actuator to change the gap d between the electrodes and the L, the ceramic pipe position, without changing the chamber environment. The measurement system consists of a digital oscilloscope, a 1/2000 voltage probe (model number: L7682190), a current probe (used to measure the voltage across resistor R_3), and a camera to record the lightning (plasma discharge) of the sparks within the gap.

The experiments are conducted at room temperature and pressure (r.t.p.) at 1 atm, focusing only on the ignition spark discharge and its energy. Firstly, a 12.4-litre chamber is depressurized using a vacuum pump, and then Nitrogen gas is added so that the pressure returns to room temperature and pressure (r.t.p.). The ignition spark discharge waveform data is recorded with the oscilloscope for each discharge period, in addition to the current and voltage. Then, a set of data is generated. A high-voltage power supply charges the capacitor through R_1. When the breakdown voltage of the gap is reached, the capacitor discharges across the gap, producing sparks that lead to a visible arc discharge.



(a) CRC spark plug (L = -2 mm)



(b) Proposed CCC spark plug (L = 2 mm)

Fig. 2. Ceramic pipe positions on the cathode.

Since it can be challenging to visualise precisely the energy required by the spark plugs to ignite successfully, the study has used the voltage waveform to evaluate the discharge energy. The spark energy is equated to the energy stored in the capacitor before and after the spark discharge period, without considering the energy loss. Therefore, we approximate the spark energy as the difference between the stored energy in the capacitor before discharge and the residual energy after discharge.

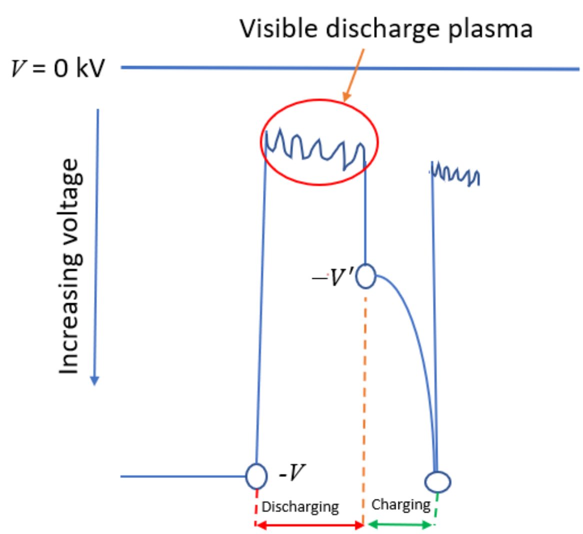


Fig. 3. Ceramic pipe positions on the cathode.

The spark discharge is produced by reducing the stored energy (charge voltage) while maintaining a constant capacitance. The spark energy (E_{spark}) is calculated using the voltage waveform. The stored energy (E_{stored}), the residual energy $E_{residual}$, and the spark energy (E_{spark}) are defined as:

$$E_{\text{stored}} = \frac{C(V^2)}{2} \quad (1)$$

$$E_{\text{residual}} = \frac{C(V'^2)}{2} \quad (2)$$

$$\text{Then, } E_{\text{spark}} = E_{\text{stored}} - E_{\text{residual}} \quad (3)$$

$$= \frac{C(V^2)}{2} - \frac{C(V'^2)}{2}$$

where V is the breakdown voltage and V' is the residual voltage after the first discharge cycle, C is the capacitance.
The efficiency of the spark plugs is computed as:

$$\eta = E_{\text{spark}} / E_{\text{stored}} \quad (4)$$

3. Results and Discussion

In both experiments, the variation in the discharge energy value was large; however, L = 2 mm had a commendable average value of 3.2 mJ. Results show that the spark energy is more stable when the cathode is immersed inside the ceramic pipe (CCC) compared to the conventional spark plug (CRC). It is shown that the discharge waveforms of the two igniters are similar, with L = -2 mm and L = 2 mm. Hence, their results can be compared. They all exhibit observable arc discharge within the electrode gap. Due to the high resistance in the circuit, a hotspot is sometimes observed on the conventional spark plug but not on the novel type. Figure 4 shows a typical voltage waveform obtained using an Oscilloscope. The discharge energy in this article refers to the energy released between the electrode gap during the discharge period (see Fig. 4).

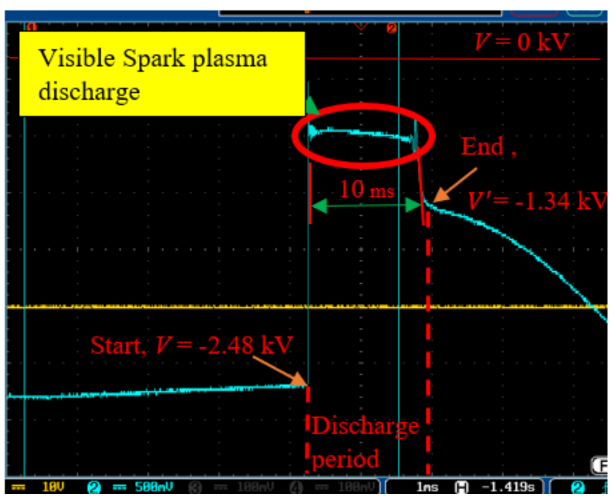


Fig. 4. Voltage waveform of the observable contact arc plasma between the electrodes during the discharge period on the CRC.

The arc plasma discharge stages were examined. Results show intense spark discharge for the novel compared to the conventional arrangement. The plasma for the CRC is often observed to initiate with corona discharge in many cases. However, when the applied voltage is increased, a single arc column is observed. The plasma is observed to have many paths when striking the anode. Different paths can damage the anode, which leads to misfiring in the long run. In addition, the plasma can be composed of whitish and purplish colours, hitting the anode at different points. The plasma colours highlight their temperatures. Figure 5 shows the plasma discharge for the CRC, where it emerges on the upper side of the cathode. Repeating such discharges from a single point will result in wear and tear of the electrode.

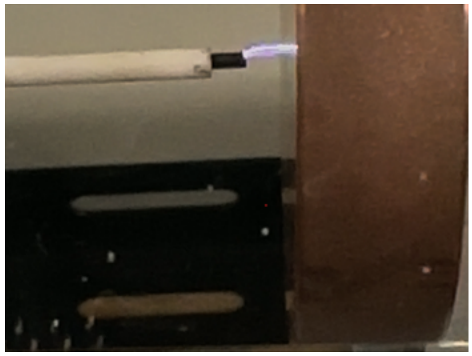


Fig. 5. Discharge for the CRC.

The plasma discharge stages for the novel CCC spark plug begin with a single-column discharge and transition to a double-column or multiple-column discharge. It is observed that the plasma striking position on the anode is almost steady for the novel spark plug. In most cases, the double column can change to a full electrode discharge without a change in the applied voltage, as shown in Fig. 6.

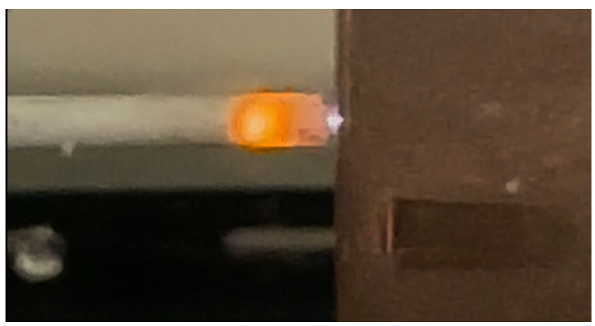


Fig.6. Discharge plasma for the CCC.

In addition, due to the creeping surface, the size of the plasma thickening occurs in a minimal amount of time, highlighting a built-up discharge that can produce multiple plasmas of the same or different sizes, all of which have a whitish colour.

Using Eq. 3, the energy of the two spark plugs is compared. The CRC plug has shown a larger spark energy, ranging from 2.5 mJ to 6.9 mJ, compared to the CCC plug, which ranges from 1.9 mJ to 4.5 mJ. They all have a higher variation; for CCC, the average energy is 3.2 mJ, while it is 4.5 mJ for CRC. For CRC, the spark energy deviation exceeds 2 mJ, whereas for the CCC plug, it is less than 1.5 mJ. Since the 1.9 mJ for the CCC plug ensures ignition just as the 2.5 mJ for the CRC plug does, it can fulfil the complete combustion energy requirement of the air/fuel mixture; hence, the CCC plug is commendable. The spark plug energies are compared in Fig. 7.

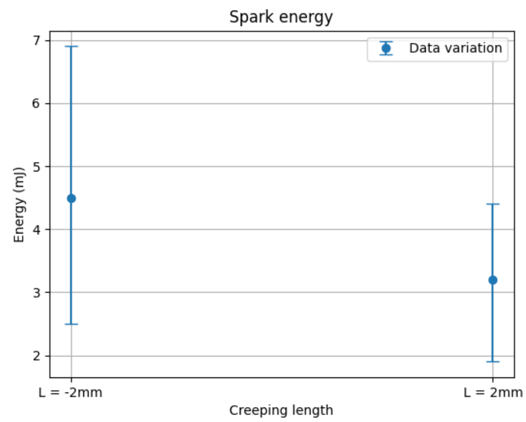


Fig. 7. Spark energy.

The energy stored in the capacitor before discharge and the spark energy (Eq. 4) are used to calculate the energy efficiency of the spark plugs. Both spark plugs exhibit relatively low efficiencies, ranging from 5% to 34%. The efficiency ranges from 5% to 30% for the CRC. This is also true for the CCC, which varies between 10% and 34%. This gives the CCC an advantage, as the minimum required spark energy efficiency is 5% higher than the CRC's. The table below shows a reduction in ignition energy for the CCC compared to the CRC.

Reducing the required energy for ignition will reduce the system sizes while ensuring sparks for ignition and complete combustion and improving energy efficiency. Hence, the CCC spark plug is recommended as a replacement for the existing CRC for this study. Table 1 shows the energy range for both spark plugs.

Table 1. Spark's energy comparison.

	The CRC	The CCC
Maximum	6.9 mJ	4.3 mJ
Average	4.5 mJ	3.2 mJ
minimum	2.5 mJ	1.9 mJ

Considering the wide spark energy variation for the CRC and recognising that the CCC's energy falls within the lower range for the CRC (see the red circle in Table 1), we can conclude that CCC will ensure ignition. However, further research is needed to ensure that CCC's energy range falls entirely within the minimum and average energy ranges for the CRC spark plug.

5. Conclusion

In this work, we studied the effect of creeping discharge on spark plugs. The ignition was observed for CRC and CCC spark plugs. We proposed a new energy measurement method. The ignition energy was quantitatively evaluated using the voltage stored in the capacitor before and the remaining voltage at the end of the spark discharge. The ceramic pipe initiates the creeping process, generating more ignition spark from a 1.9 mJ. The CRC spark plug exhibits an enormous energy variation of more than 4.4 mJ, whereas the CCC spark plug shows a less than 2.4 mJ variation.

Acknowledgements

The authors are indebted to Mr. Hino and Mr. Okuyama for their valuable input on the experimental design and data acquisition.

References

[1] E. M. Bazelyan and Y. P. Raizer, *Spark discharge*. Boca Raton, New York Washington, D.C: CRC Press Taylor & Francis Group, 1998.
[2] Y. Fu, P. Zhang, J. P. Verboncoeur, and X. Wang, "Electrical breakdown from macro to micro/nano scales: A tutorial and a review of the state of the art," *Plasma Res. Express*, vol. 2, no. 1, 2020.
[3] A. J. Wallash and L. Levit, "Electrical breakdown and ESD phenomena for devices with nanometer-to-micron gaps," *Reliab. Testing, Charact. MEMS/MOEMS II*, vol. 4980, p. 87, 2003.
[4] R. S. Benson and N. D. Whitehouse, *Internal Combustiion Engines Volume 1*. Oxford OX3 OBW, England, U.K.: Pergamon Press Ltd.. Headington Hill Hall, 1979. [Online]. Available: https://books.google.com/books?id=RKwgBQAAQBAJ&pgis=1
[5] N. Docquier and S. Candel, "Combustion control and sensors: A review," *Prog. Energy Combust. Sci.*, vol. 28, no. 2, pp. 107–150, 2002.
[6] T. V. Top and O. Lesaint, "Streamer initiation in mineral oil part II: Influence of a metallic protrusion on a flat electrode," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 9, no. 1, pp. 92–96, 2002.
[7] S. J. Laihonen, U. Gäfvert, T. Schütte, and U. W. Gedde, "DC breakdown strength of polypropylene films: Area dependence and statistical behavior," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 14, no. 2, pp. 275–286, 2007.
[8] B. R. Singh and O. Singh, "Global Trends of Fossil Fuel Reserves and Climate Change in the 21st Century," *Fossil Fuel and the Environment*, InTech, 2012.
[9] Z. Yue and H. Liu, "Advanced Research on Internal Combustion Engines and Engine Fuels," *Energies*, vol. 16, no. 16, 2023.
[10] P. Shayler, F. Atzel, and C. Bae, *Internal Combustion Engines Improving Performance, Fuel Economy and Emission*. Sawston, Cambridge CB22 3HJ, UK: Woodhead Publishing Limited, 2011.
[11] W. W. Pulkrabek, "Engineering Fundamentals of the Internal Combustion Engine," *J. Chem. Inf. Model.*, vol. 53, no. 9, pp. 1689–1699, 2013.