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Study of the Gap Discharge Phenomenon Based on Three-Dimensional Fractal

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Abstract: The damage of arc to gas insulation protection will affect the safe and stable operation of power system seriously in the field of high voltage insulation. Therefore, it is a great theoretical value and practical significance to study the mechanism of gas discharge and find out the law of gas discharge under different conditions for ensuring the safe and stable operation of power system. In order to study the variation law of arc channel complexity under different voltage levels, this paper adopts the discharging experiment of needle-plate electrode, adds different high voltage to the needle-plate electrode under other conditions unchanged, carries out many experiments, and collects five groups of discharging channel plans of needle-plate gap under different voltage. The are discharge channel image in the experiment is restored to the three-dimensional image from the space angle, and the fractal dimension of arc discharge channel under different voltage pressure is calculated by box dimension method of fractal dimension. The results show that the complexity of discharge channel decreases with the increase of voltage level, that is, the lower the voltage level and the larger the fractal dimension.

Keywords: Arc Discharge, Needle-Plate Electrode, Three-Dimensional Image, Fractal Dimension

1. Introduction

Arc is a discharge phenomenon caused by breakdown of insulating medium by voltage. Sparks generated by arcs are used to make gas igniters, lighters, etc. High temperature generated by arcs is used to make high-power arc furnaces to melt metals, and it's play an important role in industrial production and manufacturing. However, the aging or damage of insulating layer caused by long-term on-load operation, overload or external forces of cable will produce arc phenomenon. It will cause serious harm to the safe and stable operation of power system [1, 2]. Therefore, The study of arc correlation characteristics is of great significance for improving industrial production efficiency and ensuring the safe and stable operation of power system.

Arc generation is a complex process, which produces fast, complex and irregular shapes, and sometimes accompanied by bifurcation. In the power system, the more complex the arc, the greater the impact on the power system. The complexity of arc is related to voltage, air pressure, humidity and gas type. This paper focuses on the relationship between arc complexity and voltage level. Because the arc discharge process is very complex, the traditional geometry can not describe the arc discharge process [3], but the emergence of fractal theory has largely solved this problem, providing a new method for studying the arc complexity.

In 1984, Niemeyer, Pietronero and Wiesmann established the fractal dielectric breakdown (NPW) model, which opened a precedent for exploring the law of dielectric discharge based on the non-linear theory [4]. In 1999, Veldhuizen et al. used ICCD high-speed camera to collect corona images under 25 mm air gap, and obtained the phenomenon of track bifurcation of discharge channel and the effect of applied voltage. In 2004, Dulan et al. used the calculation method of three dimensions to analyze the discharge channels [5, 6].

The research on discharge phenomena by fractal theory in China is relatively late [7]. Most of them are based on two-dimensional plane, and use fractal dimension to calculate and study the complexity of arc. However, only considering the plane, the characteristics of discharge channels in the three-dimensional space can not be accurately reflected. In this paper, the discharging process is simulated by the tip-to-plate gap discharge model. Five sets of discharging channel plans under different voltages are captured by high definition video recorder. The three-dimensional image of arc channel is restored from the space angle, and the fractal dimension of arc channel under different voltage levels is calculated by box dimension method. Finally the law of the complexity of arc discharge channel under different voltage levels is found.

2. Experiment on Short Gap Discharge of Needle-Plate Electrode

2.1. Experimental Device

The experimental device consists of four parts as a whole: (1) configuration of power supply; (2) configuration of discharge circuit; (3) configuration of trigger switch; (4) configuration of image acquisition; the general schematic diagram of the experimental part of this paper is shown in Figure 1.

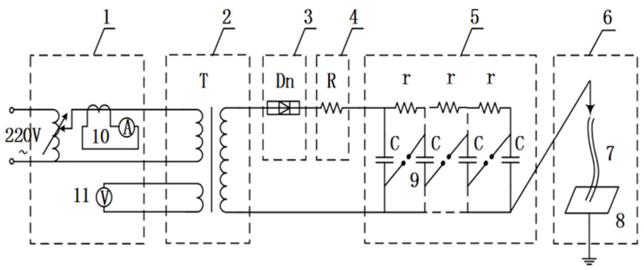


Figure 1. *Experimental schematic diagram.*

1. Control box, 2. Test transformer, 3. High voltage silicon stack, 4. Current limiting resistance, 5. Marx generator (r-resistance, C-Capacitance), 6. Tip electrode, 7. Arc, 8. Plate electrode, 9. Trigger gap, 10. Over current protection device, 11. High voltage measurement and indication

2.1.1. Configuration of Power Supply Part

This part consists of power control box (TDSB-5KVA/50KV), test transformer (5KA/50KV oil-immersed test transformer), high voltage silicon stack (2DL-300KV) and a current limiting resistance.

In the experiment, the power supply is input into the voltage operating box. After the voltage regulation of the autotransformer, the stable voltage is input to the primary winding of the test transformer. Based on the principle of electromagnetic induction, the output voltage of the two winding is high. After the output power frequency high voltage is rectified by high voltage silicon stack and filtered by capacitor, the output DC high voltage is transmitted to the discharge part through the current limiting resistance.

2.1.2. Configuration of Discharge Circuit

Due to this experiment mainly explores the discharging phenomena in the gap between the tips, it is very convenient to observe the discharging between the tips by using Marx generator as a high voltage electrode. Marx generator is a high-voltage device which generates high-voltage pulse through low-voltage DC power supply. Its capacitors are charged in parallel and discharged in series. The device was put forward by Erwin Otto Marx in 1924 [8]. Because it can imitate the process of lightning and switching overvoltage, it is often used in insulation impulse withstanding voltage, dielectric impulse breakdown, discharge and other experiments.

2.1.3. Configuration of Trigger Switch Part

In order to cause the first switch discharge of Marx generator, the method of adding electrodes or igniting gap and cathode by ionizing radiation is basically adopted. For all other discharge switches, breakdown occurs one after another due to overvoltage of discharge gap. The field distortion switch is selected as the trigger switch, which places the trigger electrode in the middle plane of the switch electrode. The trigger electrode is used to distort the external electric field when the pulse voltage is applied, so that the switch can be broken down more easily.

2.1.4. Configuration of Image Acquisition Part

The instruments of this experiment include a ICCD, it's a high-definition camera, needle-plate electrode discharge device and two reflectors, which are fixed at 10cm away from the needle-plate electrode respectively and perpendicular to each other. The distance between the high definition camera and the needle-plate gap is 200 cm (it is proved by experiments that the arc light scattering can be minimized when the distance between the video equipment and the needle-plate gap is 200cm). The experimental device is shown in Figure 2.

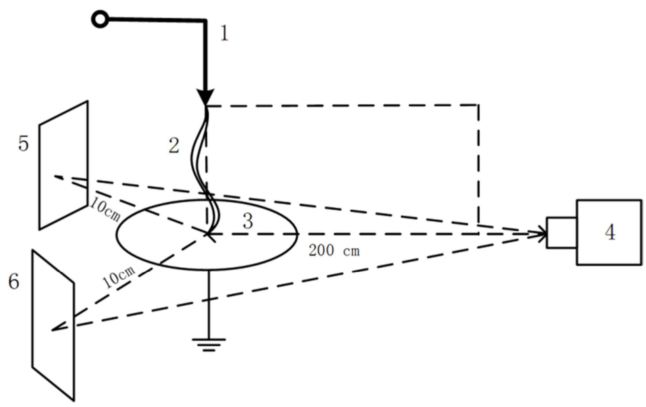


Figure 2. *Schematic diagram of image signal acquisition.*

1. Needle electrode, 2. discharge arc, 3. plate electrode, 4. ICCD, 5. reflector 1, 6. reflector 2 (90° angle between reflector 5 and 6)

2.2. Experimental Principle

The experimental process of simulated discharge was photographed by ICCD device, and the two-dimensional image of discharge channel was extracted. The variation of arc image area with time was studied quantitatively [9]. Due to the discharge arc is generated in three-dimensional space, the plane arc images in two perpendicular directions of the same discharge arc are captured by optical principle, and the three-dimensional coordinate information of the arc is restored by combining the two directions of the plane map.

3. Image and Analysis of Needle-Plate Discharge Arc

3.1. Fractal Dimension

3.1.1. Introduction to Fractal Theory

About two thousand years ago, Euclid created a very useful geometry in the third Century B. C. Although differential geometry and projective geometry were born in the subsequent development, Euclidean geometry played an irreplaceable role in life and scientific research. Euclidean geometry mainly focuses on the relationship between points, lines and planes. However, with the rapid development of science, a large number of new theories and new research fields have emerged. Traditional geometry has been difficult to describe some very complex and irregular phenomena in nature, such as the study of crystal cracks and the calculation of complex Coastline Length [10, 11]. It also includes some graphics conceived by mathematicians, such as Voncock Curve, Cantor Tripartite Set, Hilbinsky Triangle and so on.

In 1975, Mandelbrot proposed the concept of fractal first [12]. Fractal is the meaning of fragments, but literally, it does not fully explain the concept of fractal geometry. After mathematical discussion and induction, it is generally believed that an important morphological feature of fractal is the filling space in the form of non-integer dimension, which can be understood as "fragmentary, non-linear, decimal". Iterative generation and self similarity are two important principles of fractals. It is specifically expressed as [13, 14]

(1) under the change of normal scale, the property of geometry will not change, that is, scale invariance.

(2) because of the reason of iteration, the geometry has infinite fine structure at any scale.

(3) due to the self-similarity, that is, starting from the symmetry of different scales, fractals can be generated recursively.

Take the famous Koch curve as an example [15]. Its construction process is roughly as follows: assuming a straight line segment of L length, it is evenly divided into three parts, each of which has a length of L/3, in which the line segments on both sides remain unchanged, the middle line is removed and replaced by two straight lines of the same length, and the two straight lines are 60 degrees apart, and each straight line is horizontal. The angle of the position is also 60 degrees, and the figure is equal to the equilateral triangle without bottom edge. At this time, repeat the above operation, and separate the four new straight lines with L/3 length. The middle line segment is also replaced by the equilateral triangle with bottom edge. Repeat the above operation until infinite. Through this iteration method, a self-similar structure curve, namely Koch curve [16], can be finally obtained. As shown in Figure 3.

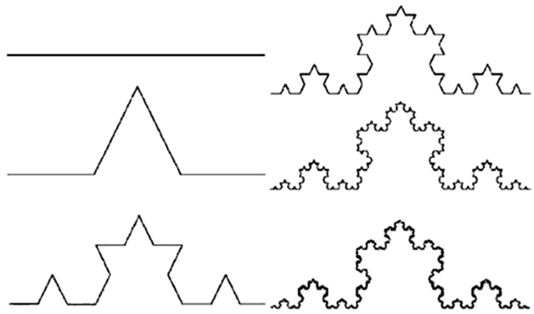


Figure 3. *Koch curve.*

For this mathematical model with strict self similarity, it's a regular fractal model. However, the self-similarity of some irregular fractal phenomena in life is often derived from statistical significance, which random fractal phenomena. Every substance with self-similarity often conforms to the scaling invariant characteristic, that is, arbitrarily select the small area of the substance, enlarge or shrink the area and then have the same characteristics as the whole. Therefore, if an object has fractal characteristics and intercepts a part at will, the random characteristics and complexity of the part are consistent with the whole.

By comparing Euclidean geometry with fractal geometry, it can conclude that Euclidean geometry studies some conventional invariants, such as length, area and volume, which are mainly applicable to the products of human civilization. Fractal geometry studies some complex objects or phenomena in nature. Unlike Euclidean geometry, fractal geometry regards points, lines and surfaces as a continuous process of development. The common two-dimensional and three-dimensional plane do not exist separately from each other.

As a new system of modern mathematics, fractal theory has been used in coastline description, signal processing, image coding theory and other fields, and has made remarkable achievements. Fractal geometry has been proposed to the present, but in just a few decades, it is just in the ascendant. In the future scientific research and production application, fractal theory will be used more widely.

3.1.2. Calculation of Fractal Dimension

The fractal dimension is an important parameter describing the chaotic attractor singular degree, it can reflect the basic characteristics of fractal system, is often used for the digital characteristics of the nonlinear system and fault diagnosis etc. The common fractal dimensions include box dimension, correlation dimension, Lyapunov dimension, Hausdroff dimension and so on. In this paper, using the box dimension method to calculate the dimension of arc discharge channel.

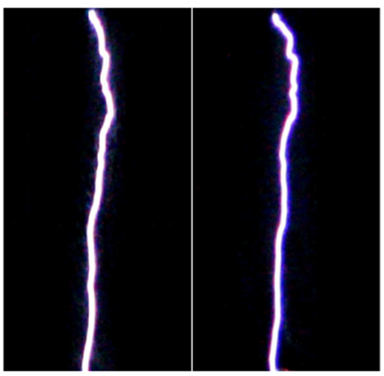
The general idea of box dimension method is to cover the objects to be studied with the infinitely small square of the side length. If A is a set of bounded points on a plane, according to the boundedness of A, a rectangle that contains A completely can be always found. If the rectangle is divided into many small squares with side lengths is ε, and ε approach zero, there must be small squares containing points in A. The number of small squares containing points in A is counted as $N(\varepsilon)$. Using D to represent the fractal dimension of the studied object, so, the formula is

$$D = \lim_{\varepsilon \to 0} \frac{\ln[N(\varepsilon)]}{\ln \frac{1}{\varepsilon}} \tag{1}$$

This formula is not only limited to the research object on the plane, but also applies to multidimensional space. If the object of study is a line segment, the measurement scale mentioned in the formula can be understood as a line segment with length a. If the object of study is a two-dimensional area on a plane, the measurement scale can be understood as a square with side length a. If the object of study is a three-dimensional space, the measurement scale can be understood as a square with side length *a*. And the multidimensional dimension calculation according this method can got. The fractal dimension can be an integer or a decimal.

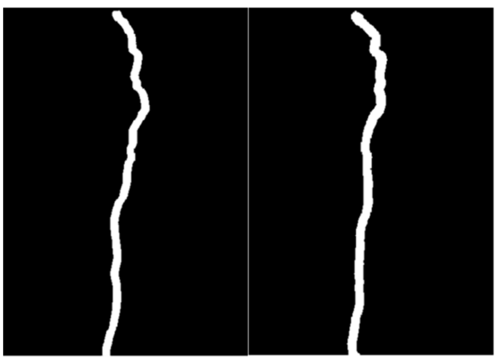
3.2. Box Dimension Calculation of Three Dimensional Arc

When analyzing the image obtained in the experiment by using the three-dimensional fractal program, the high-speed video is first decomposed into frame sequences by using KMplayer video processing software, and then the left arc is intercepted as X direction, and the right arc is taken as Y direction and the rectangular coordinate system is established. Because of the strong scattering of arc light, image denoising and binaryzation processing are needed first [17, 18]. The original image and processed image in X and Y direction are shown in Figure 4 and Figure 5.



(a) X direction (b) Y direction

Figure 4. *Original image.*



(a) X direction (b) Y direction

Figure 5. *Processed image.*

After getting two valued arc diagram processed in X and Y direction, the three-dimensional coordinate system of space is established by MATLAB, and the coordinates of the central axis of X direction and Y direction arc are obtained by using the method of weighted average, and the three-dimensional coordinates of arc are constructed by combining Z axis. The restored three-dimensional image is shown in Figure 6.

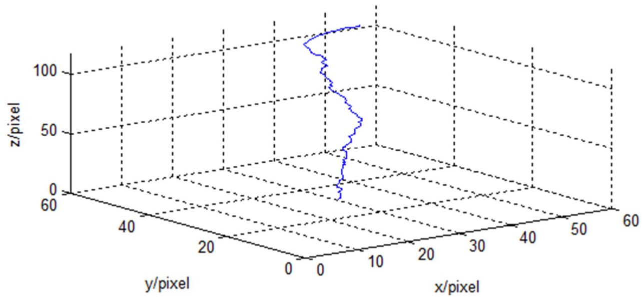


Figure 6. *Three dimensional diagram of arc.*

The box dimension of Figure 5 is calculated by box dimension method, and the result is shown in Figure 7.

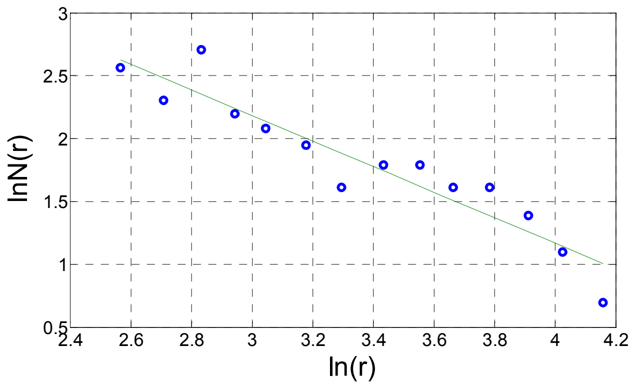


Figure 7. *Relationship between measurement scale and box quantity (D=1.0172).*

The fractal dimension of the arcing channel is D=1.0172 by fitting the slope of the straight line in Figure 7.

According to the theory of fractal dimension, fractal has self-similarity and infinite fineness, which means that the bigger the fractal object is, the better it is. When the fractal object reaches infinity, it is the ideal state of fractal. In the fractal dimension program of this paper, the fractal of arc can not cover all areas, so the number of fractal and the fractal range is self-set. This means that the different fractal results will got if take different fractal times or intercept different fractal ranges. There are some errors between the experiment results and the ideal results [19, 20].

The first error can not be eliminated in theory, but for the second error, if appropriate methods are adopted, the calculated results can be closer to the true value. The initial run of the three-dimensional program does not know the specific size settings, but you can set a rough range. After the first run of the program, the position of the set value can be observed according to the logarithmic coordinate diagram of box size and box numbers presented. In theory, the fitting straight line should be in a downward trend, so the upward trend in the curve mentioned above should be discarded, and the remaining downward trend should be taken as smoothly as possible, so that the results are closer to the complexity of the arc itself. It is feasible to find an optimum start size and an optimum end size by changing the settings several times.

3.3. Box Dimension Calculation of Two Dimensional Arc

In order to show the difference between three-dimensional fractal and two-dimensional fractal, the two-dimensional fractal of arc is calculated after three-dimensional fractal. Two-dimensional fractal is only used plane images taken in two directions. The experimental results are shown in Figure 8 and Figure 9.

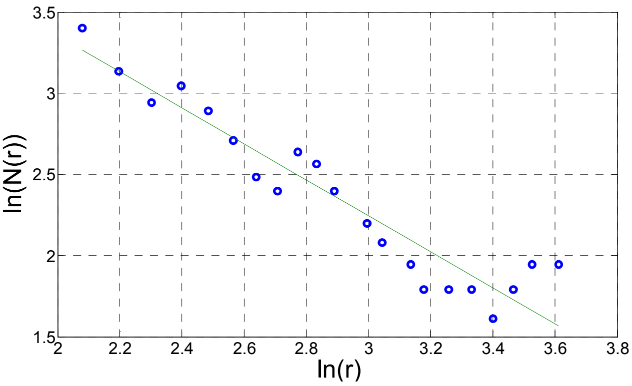


Figure 8. *Relationship between measurement scale and box quantity (X direction, Dx= 1.1171).*

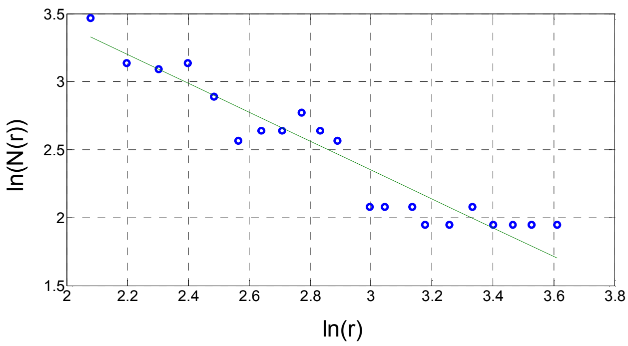


Figure 9. *Relationship between measurement scale and box quantity (Y direction, Dy=1.0718).*

3.4. Comparison of Three-Dimensional Fractal and Two-Dimensional Fractal Results

Compared with Figures 7, 8 and 9, it can be found that the arc dimension Dx = 1.1171 in X direction and Dy = 1.0718 in Y direction are different from the arc dimension D = 1.0172 obtained by three-dimensional fractal. From the experimental results, compared with the three-dimensional fractal, the two-dimensional fractal can only obtain the fractal dimension of X direction and Y direction separately, but the dimension of the two directions can not reflect the complexity of an arc in the three-dimensional space; the three-dimensional fractal combines the overall idea, and simultaneously observes and analyses the arc from different angles. Undoubtedly, the latter can reflect the essence of arc shape better.

4. Experimental Results and Analysis

4.1. Relationship Between Fractal Dimension of Arc Channel and Voltage Level

In order to determine the correlation between the complexity of arc channel and voltage level, 50 groups of discharging experiments under five different voltage levels (90kV, 100kV, 110kV, 120kV and 130kV respectively) were conducted. The three-dimensional fractal dimension of each voltage level is calculated and counted, and the relationship between voltage level and arc dimension is obtained as shown in Figure 10.

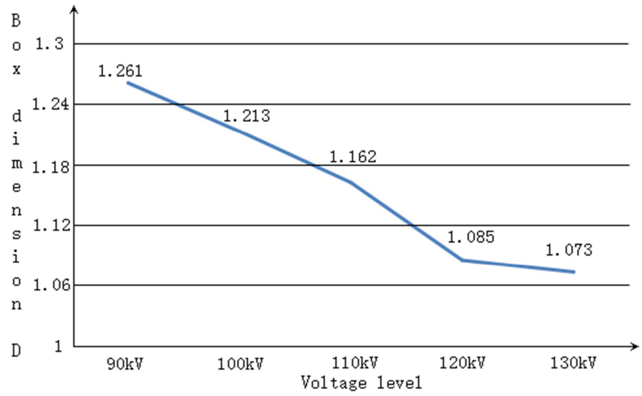


Figure 10. *Relationship between voltage level and arc dimension.*

From Figure 10, it can be seen that with the increase of voltage level, the box dimension D of arc channel shows a downward trend, that is, the lower the arc complexity is, when other parameters remain unchanged and the experimental environment is the same.

4.2. Experimental Analysis

Suppose that under the action of electric field, electrons collide with neutral particles, and the kinetic energy lost by electrons in each collision process is

$$f = \frac{8}{3}\frac{Mm}{(m+M)^2}(1-\frac{\Omega}{u}) \approx 2.66\frac{m}{M} \tag{2}$$

According to the law of conservation of energy, if the electrons are dispersed by electrons and the electrons move *dx*, under the action of electric field, the energy relation is as follows

$$edu = eEdx - \frac{feudx}{s} \tag{3}$$

S is the distance that electrons move along the electric field in unit time.

$$s = 0.5\lambda^2\frac{E}{u} \tag{4}$$

$$\frac{du}{dx} = E - 5.32\frac{mu}{M}\frac{u-\Omega}{\lambda^2 E} \quad (5)$$

For equilibrium, energy gains and losses are equal, so, $\frac{du}{dx} = 0$, The relationship between electric field intensity and u at this time can be obtained is

$$E = 5.32\frac{mu}{M}\frac{u-\Omega}{\lambda^2 E} \quad (6)$$

The u at this time is equal to U_T, that is

$$\begin{aligned} U_T &= \frac{1}{2}\Omega + \sqrt{\frac{\lambda^2 ME^2}{5.32m} + \frac{\Omega^2}{4}} \\ &\approx \frac{\lambda E}{2.31}\sqrt{\frac{M}{m}} = \frac{0.707E\lambda}{\sqrt{f}} \end{aligned} \quad (7)$$

As all know form equation (7) and $\frac{1}{2}mc^2 = eU_T$

$$c = \left(\frac{1.414eE\lambda}{m\sqrt{f}}\right)^{\frac{1}{2}} \quad (8)$$

So, the electron mobility is

$$K_E = \frac{0.92le\lambda}{mc} = 0.755\sqrt{\frac{e\lambda\sqrt{f}}{mE}} \quad (9)$$

From the above formula, it can be concluded that the electron mobility K_E is inversely proportional to the electric field strength E, that is, the higher the electric field strength is, the lower the electron mobility is.

The needle plate electric field used in this experiment is one of the most typical extremely uneven electric fields. In a extremely uneven electric field, the higher the voltage applied to the needle electrode, the greater the electric field intensity.

The electron mobility K_E is in inverse proportion to the electric field intensity E. Therefore, when the electric field intensity is greater, the number of electrons migrated is less. For discharge channel, the higher the threshold voltage, the fewer points for development, the lower the tortuosity of discharge channel and the smaller the fractal dimension; the lower the threshold voltage, the more points for development, the greater the tortuosity of discharge channel and the larger the fractal dimension.

5. Conclusion

Using fractal box dimension as the theoretical basis in this paper, starting from the three-dimensional perspective, the reduction in arc channel in the three-dimensional space, analyzed and calculated the variation of arc dimension under different voltage level, draw the following conclusions.

For the discharge arc at the same space, the result of two-dimensional fractal dimension is obviously different from that of three-dimensional fractal dimension. The results of three-dimensional fractal dimension are closer to the actual dimension of arc.

With other parameters unchanged, with the increase of voltage level, the dimension of arc channel box shows a downward trend, that is, the complexity of space arc will be reduced.

In this paper, the box-counting dimension is used to calculate the box-counting dimension of space arc, and it is disturbed by some external light and noise during the shooting process. In the follow-up study, more algorithms can be added to further reduce the external interference, so that the calculation conclusion is more accurate.

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