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Research Article

Study on the Fractal Dimension and Growth Time of the Electrical Treeing Degradation at Different Temperature and Moisture

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The paper aims to understand how the fractal dimension and growth time of electrical trees change with temperature and moisture. The fractal dimension of final electrical trees was estimated using 2-D box-counting method. Four groups of electrical trees were grown at variable moisture and temperature. The relation between growth time and fractal dimension of electrical trees were summarized. The results indicate the final electrical trees can have similar fractal dimensions via similar tree growth time at different combinations of moisture level and temperature conditions.

1. Introduction

Electrical treeing is a typical degradation mechanism in polymers. Insulation fault can be generated in different processes as a result of operating at different electric field condition and insulation failure time [1]. Breakdown is an accident in a short time while degradation is a process to decrease the insulation class over a period of time [2].

The analysis of electrical trees is important due to the faulty insulation in polymers. Electrical treeing can lead to breakdown of the polymers due to the electric field strength. Electrical treeing occurs in weak parts of the polymers [2]. Electric charges around the weak parts could cause partial discharge. The PD (partial discharge) activity around weak part (as a result of void) can cause the initial electrical tree [3]. The insulation breakdown in electrical machines, HV cable insulation, switchgear, and transformer bushings can be triggered by electrical treeing [4]. According to the quality control of manufacturing industry, the insulator of a cable can contain residual water, contaminates, and void [5]. A typical electrical tree in underground cable insulator could grow from the electrode asperities gradually until final breakdown. The faulty insulation in the polymers of this cable could cause a short circuit between the inner and outer conductors.

Fractal is a kind of shape parts, which have self-similar properties to the whole [6]. Mandelbrot was the first to use fractal to describe complex images in [7, 8]. The fractal can be classified as regular and natural. The regular fractal is mathematics conception such as Koch curve [9] and Sierpinski sieve [10]. Fractal dimension can be used to describe the complexity of natural shapes. In Euclidean geometry, straight lines and curves are one-dimensional and planes and circles are two-dimensional. However, the Euclidean dimension could not well describe the mathematic conception fractal. Hence, a Hausdorff–Besicovitch Dimension was used to describe the dimension of fractal [11]. The dimension is defined using minimum spheres to cover images.

The analysis of fractal dimension could reveal characteristics of electrical trees. Electrical trees growth has self-similar properties, and the properties are the basic theory of fractal [12]. The electrical trees often finally indicate by several of types which is completely similar on fractal dimension by facts include temperature [13, 14], voltage frequency [15], composited voltage [16], and aged materials [17]. The fractal dimension describes the density of images in some way. Electrical trees are generally classified as branch, bush, and bush-branch trees by fractal dimensions, and the fractal dimension is actually the branch density [18, 19].

In this paper, we aim to understand how the fractal dimension and growth time of electrical trees changes with different temperature and moisture.

2. Sample Preparation

2.1. Needle-Plane Samples. Electrical treeing test is used to analyse electrical trees characteristics. A typical electrical tree can grow from the electrode asperities. The test is usually processed in a needle-plane sample, and the needle is used to simulate an initial electrical treeing condition as show in Figure 1. A tungsten carbide needle is embedded in the middle of the sample. A high voltage can be applied to this needle. The sharp needle point can simulate the "weak parts" in polymers. The shank diameter and radius of curvature of this needle are 1 mm and 3 μm, respectively. The distance between needle point and the plane is 2 mm. The electrical trees can grow in between needle point and plane.

Araldite CY1311 was selected to make block epoxy resin samples. The 30 g epoxy resin CY1311 and 10 g hardener were measured into two beakers via a balance, respectively. The 40 g solution was calculated a little bit more than mould volume multiplied by density of epoxy resin (1 g/ml) via taking an integer. Hence, mixed solution was just enough to pull into the mould. The little amount of hardener was left inside the beaker while pouring into the epoxy resin. Hence, the hardener was measured little bit more than it was designed. Epoxy resin and hardener were mixed using by a stirring magnet for 10 minutes; afterwards, the two beakers were placed inside the oven at 40°C for 10 minutes. Water and air bubbles were removed from the solutions. At the same time, silicone oil was evenly applied adequate amount to the inside of the mould in order to avoid conglutination between the sample and mould. Seven needles were vertically placed in the hollow area of a concave mould. The needle-plane distance was 2 mm. Mixed sample degassed in the oven at 40°C for 10 minutes before pouring into the concave mould. After curing at room temperature for 48 hours, the samples were heated for 1 hour at 100°C for postcuring. Samples were stored in the vacuum oven for at least 2 days in order to minimize the moisture level. This moisture level was treated as 0% (initial weight of the sample) when calculating the final moisture level of these samples. At last, the long sample was cut into several one-needle blocks (Figure 2).

2.2. Water Conditions. The block samples were stored in different humidity-controlled containers before the electrical test in order to make different water conditions. The initial weight of each sample M_0 was measured. The samples were stored in four saturated salt solution containers. These four-solution lithium chloride (LiCl), magnesium chloride (MgCl2), potassium carbonate (K2CO3), and sodium chloride (NaCl) were used to create a constant relative humidity, and these relative moisture levels are 15%, 30%, 44%, and 75%, respectively, at 15°C. All samples were measured every day in the first week and every Monday till the electrical treeing experiment. Prepared samples were measured with an electronic balance and recorded in a personal computer. The mass uptake, $\Delta M\%$, is defined in Equation (1):

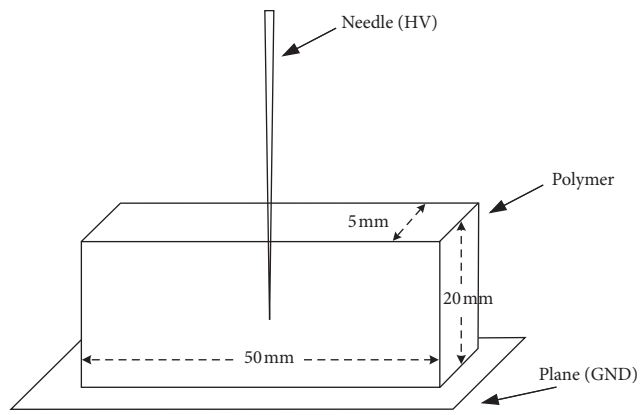


Figure 1: Needle-plane sample.

$$\Delta M = \frac{M_i - M_0}{M_0} \times 100\%, \quad (1)$$

where M_i is measured weight and M_0 is original weight of simple.

The average $\Delta M\%$ and experiment time t of each group was calculated. The graph of average $\Delta M\%$ vs. $\log(t)$ was plotted to calculate relative humidity (Figure 3).

3. Electrical Treeing Experiment

3.1. Experiment Apparatus. The center of the experimental set-up for electrical treeing experiments is a Faraday cage (Figure 4). The cage was used to exclude external noise around and prevent experimenter getting an electric shock. The white box was used to exclude light noise around. The red line above the box is connected to the positive electrode. The block epoxy resin sample was tested in the box with electric insulating oil. There are four main kinds of equipment connected to the cage including a CCD system, an oscilloscope system, a voltage system, and a temperature system.

The CCD system was used to take two kinds of pictures around the needle point. The CCD camera was controlled via a computer. The expose time of the camera can be changed via a camera program in this computer. PD light and electrical tree images were taken via changing the expose time. The lens inside the cage takes pictures and then displays them on a monitor.

The voltage system was a variac with a protective relaying device. The input voltage of the needle is controlled via the variac. Some special voltage levels were shown on a step-voltage reference table. The protective relaying device was used to disconnect the power and variac when the electrical trees break down.

The temperature system was a heater to create a constant temperature in the test cell. A small variac was used to change the input voltage of the heater. An output power controller made the temperature of heater can be controlled

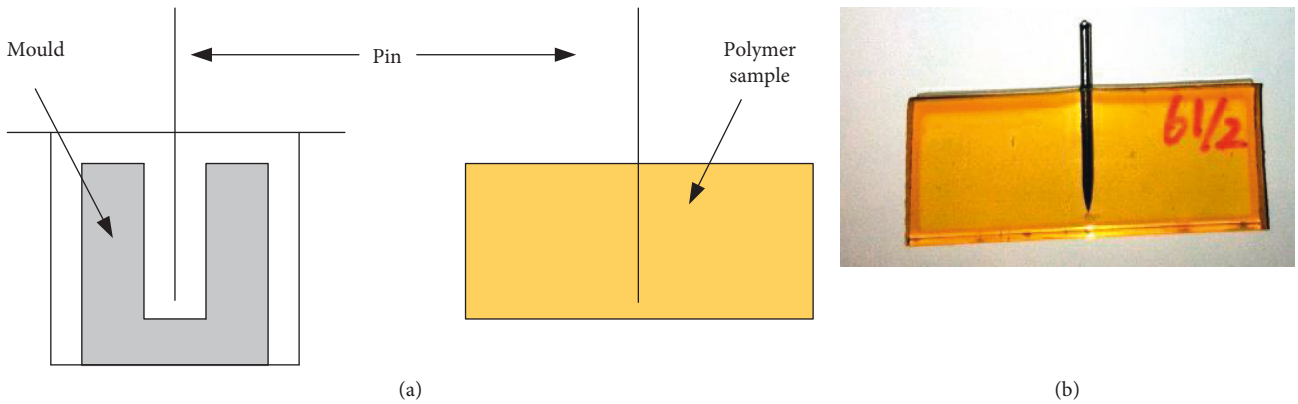


Figure 2: Epoxy resin samples preparation: (a) sample prepared by using a concave mould; (b) a block sample.

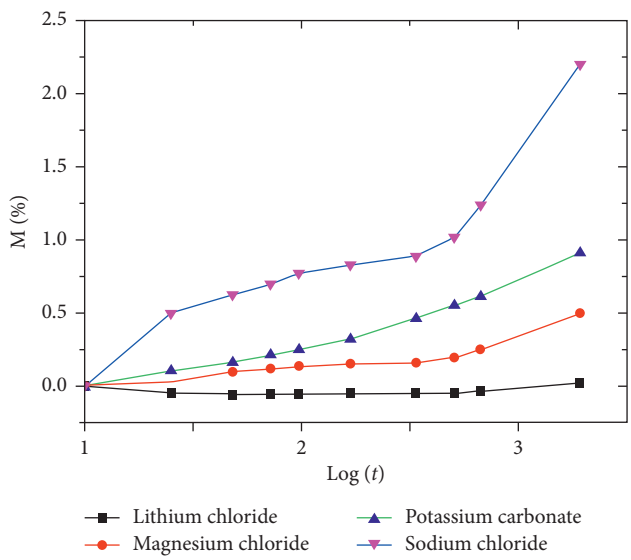
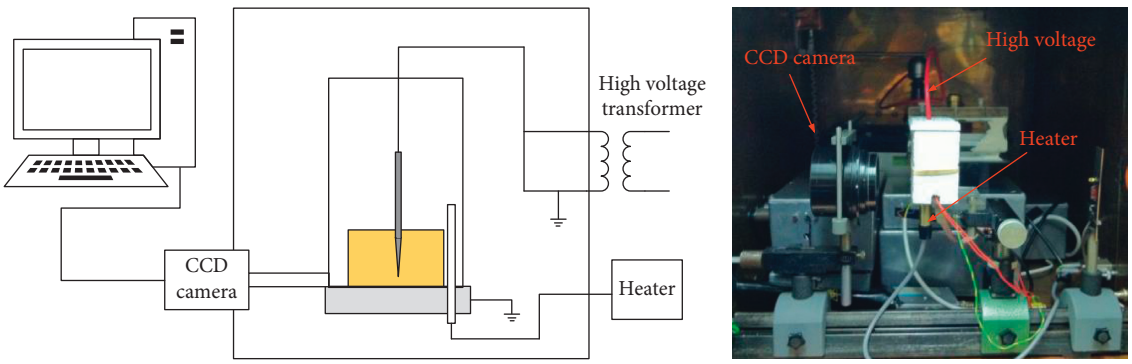


Figure 3: Plot log (t)–ΔM% of samples.

to the accuracy of 0.1°C. The temperature shown on this controller was the heater's temperature. A set-sample reference table was used to achieve an accurate sample temperature when the variac was set at 60 units.

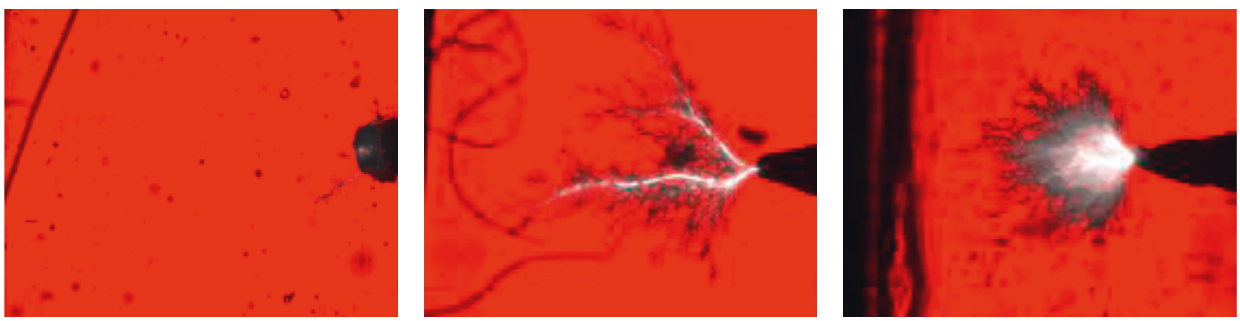
3.2. Experiment. Samples were prepared 2 months before the electrical treeing experiment. After two months of sample water conditions preparation, each sample was taken out from the containers with saturated salt solutions and measured weight before it was going to do a test. Final mass uptakes can be calculated from the last weights which were used to describe the humidity of the samples. The protruding needle was cut into 0.5 cm after being measured in order to fix in the treeing test cell. The needle point was fixed in the middle of the lens sight. A camera was used to take photos around the needle point. In order to get clear growth trees photos, a sharpest needle image was taken via changing the focus of the lens at the beginning. A typical electrical treeing model can start from charge transport. The space charge accumulated at the cute point will result in a partial discharge. This space charge combines the partial discharge that can affect electric field around. Then, the electrical trees can grow from this point. The lens focus could be changed if necessary during the test. The temperature system then began to work for at least 1 hour in order to make a right temperature for the sample. A timer was set to 5 seconds due to the timer has an approximate 5 seconds delay to the power supply. Other devices were preset during this one hour.

The experiment devices were double checked before the test in order to ensure safety. Electrical tree experiment was testing under a dark condition. Photographs around the needle point were monitored via the charged-coupled device (CCD) camera. The camera was explored every second. At the same time, a clock was stated to record the tree growth time. The explored time was changed to 10 s via the camera program in order to acquire PD light. Initial PD points position and main electrical tree branches could be found via appropriate white level of PD light images, as shown in Figure 5. Electrical tree images were taken while the electrical trees were grown. A tree is defined as a fast growth tree while the tree crosses the 1/4 in the first minute; otherwise, it is defined as a slow growth tree. The electrical



(a) (b)

Figure 4: The Faraday cage used for electrical treeing experiment: (a) diagram of the set-up; (b) photograph of the cage.



(a) (b) (c)

Figure 5: Superimposed red-white-black images of PD light and tree images with a same red and white light level: (a) initial PD point; (b) clear electrical branches; (c) complex electrical branches.

tree images were taken every one minute for fast growth trees and every two minutes for slow growth trees. Corresponding PD light images was taken 11 seconds delay because 1 second was used to change the program, and 10 seconds were used to expose. High voltage supply was cut off when the tree was grown at 2/3 needle-plane distance. Growth time distance at this needle-plane distance was treated as tree growth time.

4. Estimate Fractal Dimensions

4.1. Methods to Obtain Electrical Tree Images. 2-D electrical trees images are required to estimate fractal dimension. A microscope was used to make 2-D superimposed images. A charged-coupled device (CCD) camera mounted on a microscope was used to take digital pictures from two electrical tree samples. The pictures were taken after every 40 fine focus steps from the first clear branch to the last. The composed images were compiled by software called Montage. The distance between branches and camera lens is different. Various branches will display on the different points. The images can be taken from the top branch (branch 1) of an electrical tree to the bottom (branch k) by changing the lens-sample distance (Figure 6). Then, a superimposed image can be composed by extracting the clear parts of different camera lens images (red cycle parts).

The software named montage is used to compose those images into superimposed images. Several methods are used to estimate the fractal dimension of 2-D images in different scientific researches. For electrical trees, the fractal dimension describes the density of branches. The superimposed images (Figure 7) were used to estimate the fractal dimension of electrical trees.

4.2. Fractal Dimension Using Box-Counting Method. A Minkowski–Bouligand dimension (box-counting dimension) was used to estimate fractal images in nature. The box-counting dimension is using grids to cover images. Uniformity grids are superposed on the fractal images. The amount of covering boxes is used to estimate the box-counting dimension. The box-counting dimension is greater than or equal to the Hausdorff dimension because the minimum freedom spheres are used to cover a fractal image in Hausdorff dimension. The box-counting dimension and Hausdorff dimension are equal while all the boundaries of the fractal images are coincident with the boundaries of grids. The fractal dimension using box-counting method has been utilized in studying electrical treeing behavior in XLPE cable insulation samples [20]. The box-counting dimension can be defined as in Equation (2):

$$D_{\text{box}} = \lim_{\varepsilon \longrightarrow 0} \left(\frac{\log N(\varepsilon)}{\log(1/\varepsilon)} \right), \tag{2}$$

where $N(\varepsilon)$ is the amount of boxes and ε is the size of boxes.

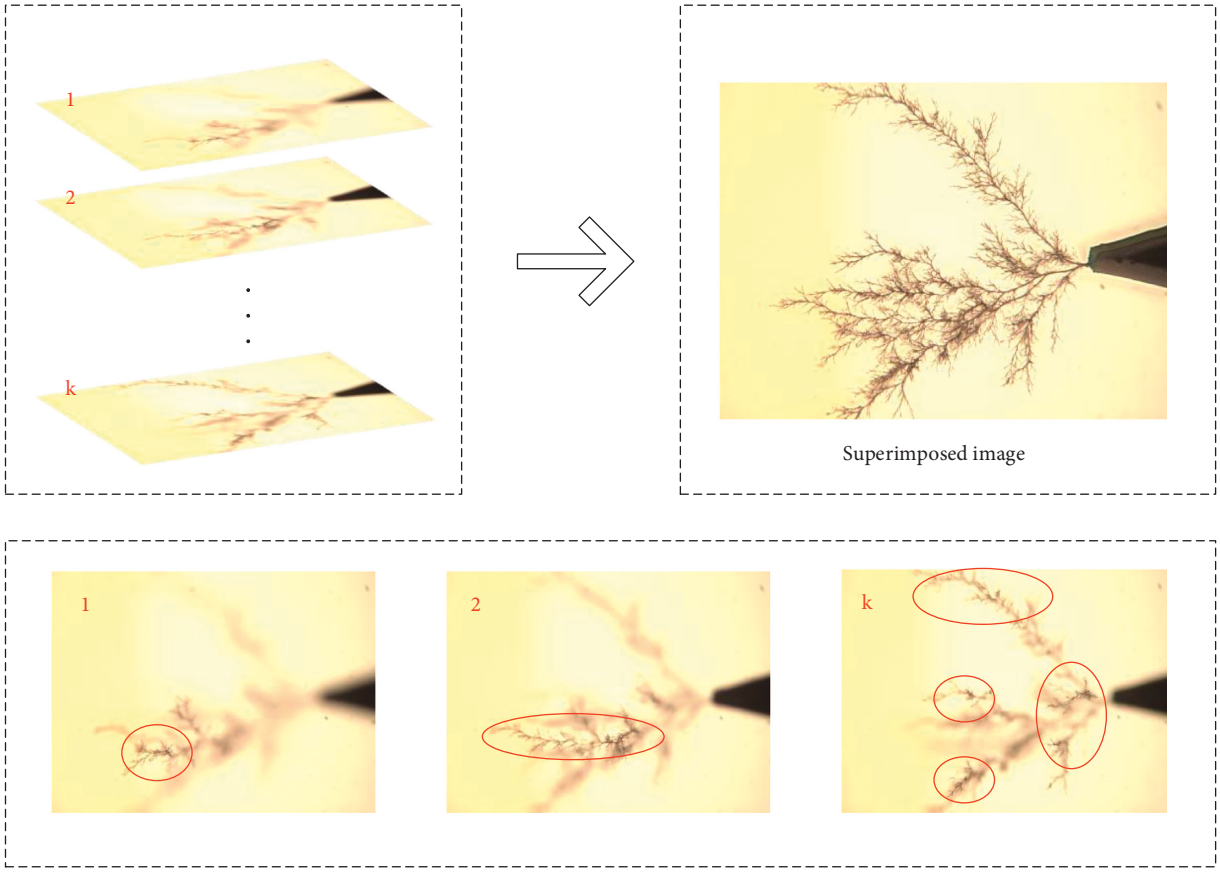


Figure 6: Schematic diagram of composing tree images.

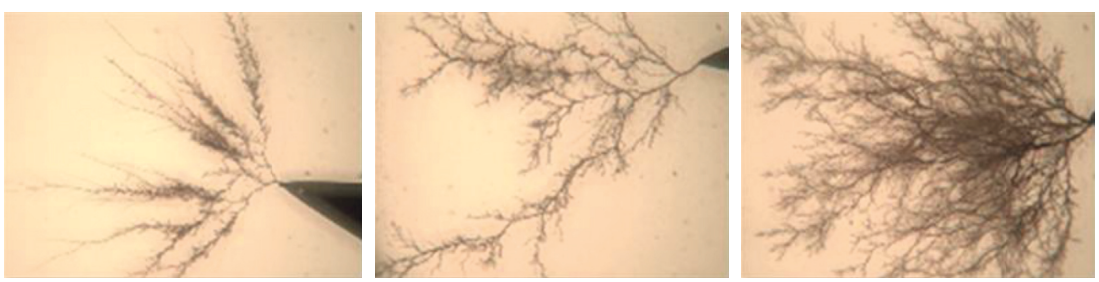


Figure 7: Superimposed images from samples.

Infinitesimal grids cannot be used to cover natural images (nonconvergence). Fractal sharps in nature mush have upper and lower limits. The fractal dimension can only be estimated between these two limits. The upper limit means the size of the grids scale must be larger than the size of the image. The lower limit means boxes scale must contain at least 1 point of the image. Groups of the amount of covering boxes can be measured with different size grids between the upper limit and lower limit. The grids are half size of the group next to it. The sizes of grids are $2n-1$ unit while the size of the minimum size is 1 unit (n is a positive integer). The box-counting dimension can be estimated via infinite approximation as in Equation (3):

$$D_f \propto \frac{1}{n}\sum_{n-1}^{n}\frac{\log N(r_n)}{\log(1/r_n)}. \quad (3)$$

The groups of results satisfy the power law. The negative exponent of the $\log N(r)$–$\log r$ fitting curve gives the box-counting dimension. Local scaling exponent (local fractal dimension) can be defined as in Equation (4):

$$D = \frac{dInN(r)}{dIn(1/r)}. \quad (4)$$

The fractal dimension of digital images is estimated using box-counting method in MATLAB. One pixel is the minimum size of boxes. Hence, one pixel is the boundary of lower limits. This process can be described as follows:

(1) A color image is converted into a grayscale image (Figure 8).

(2) The image is binarized (translate the grayscale images into white and black images) by an appropriate

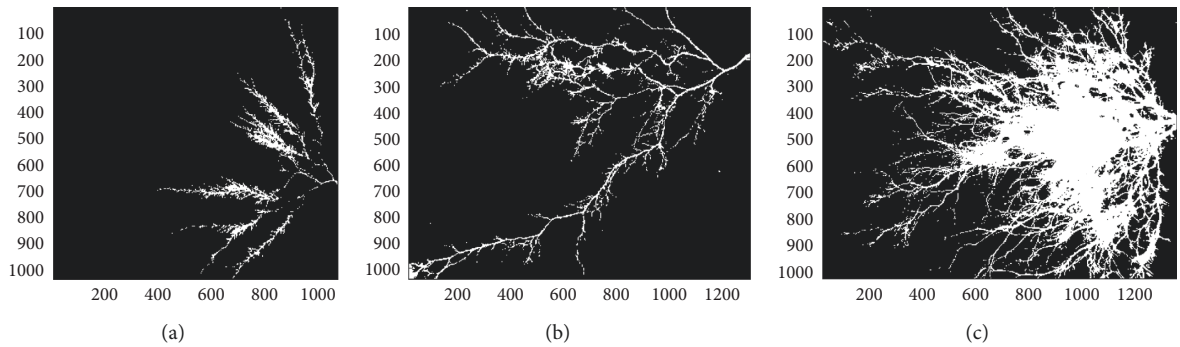


Figure 8: Brinarized images. (a) $D_f = 1.36$, (b) $D_f = 1.49$, (c) $D_f = 1.74$.

light value (the value can be set in the code) for each pixel (white pixels are binarized "electrical trees").

(3) The total number of boxes N(r) containing white pixels is calculated by different size of r.

(4) A log-log plot of N(r) curve as a function of r is indicated. The slope gives the fraction dimension.

Three groups of images are selected by the fractal dimension from low to high linearly. All binarized images can fit the original images well.

The fractal dimension increases when the fitting space decreases (Figure 9).

Local fractal dimension describes the differentiation of fractal dimension distribution curve at each r (the size of grid) point (Figure 10). Local fractal dimension curve is not smooth because local fractal dimension cannot accurately describe the self-similarity from a large size grid. At small r points, the local fractal dimension is similar. The result of fractal dimension will decrease due to these points. However, the box-counting results still describe a fractal characteristic in statistics. Hence, the slope of the $\log N(r)$–$\log r$ can give the box-counting dimension.

5. Results and Discussion

Four groups of samples {A (Table 1), B (Table 2), C (Table 3), and D (Table 4)} were stored in four saturated solution conditions (LiCl RH15%, MgCl2 RH30%, K2CO3 RH 44%, NaCl RH 75%) for two months. Samples were testing at a different moisture level of 0.03%, 0.5%, 1%, 2.5%, and different temperature at 15°C, 20°C, 25°C, and 30°C. Trees were grown at 2/3 needle-plane distance. The tree growth time was decreasing while the temperature was growing up. The degradation mechanism has change to thermal breakdown at temperature 30°C and moisture level of 2.5%.

The tree growth time was decreasing while the moisture level was rising. The lower tree growth time at moisture level of 0.03% was greater than the upper tree growth time at moisture level of 0.5%. The upper tree growth time at moisture level of 2.5% was lower than lower tree growth time at moisture level of 0.5%. Hence, the moisture level can be one of the factors to affect the tree growth time.

The variable temperature and moisture level can affect the electrical tree growth time and electrical tree types. Objectively, electrical tree growth time changes by both different absorbed moisture and temperature. Either increasing moisture level and/or temperature could make tree growth faster. The density of electrical tree was decreased while the moisture level and/or temperature increasing. The tree growth time and tree density are negative correlation (Figure 11). In Figure 12, the white light describes the different intensity and types of PD activities. The PD activities of medium-density trees were lower than the low-density trees. The PD activities indicated that how the electric charges are affected by the electric field strength. The power of electrical tree growth came from the electric strength. The electrical tree was grown fast due to the high needle-to-plane direction strength. The needle-to-plane direction strength of high-density trees can decrease significantly due the complex electric field strength.

The fractal dimensions of electrical trees were estimated using Matlab box-counting method from the superimposed images (Figure 13). The relationship between tree growth time and fractal dimension were positively correlated. The moisture level and temperature conditions of electrical treeing were used to change the electric field strength. Both tree growth time and the fractal dimension may reflect the direct influences of the electric field strength. The relationship between fractal dimension and growth time can work with electrical trees growth at the same moisture level and temperature conditions. The fractal dimension of faster growth tree was larger than slower growth trees at some environment conditions. The differences at some environment can be caused by the small differences on the internal structure and the chaos electric treeing processes. The chaos things can be described by the fractal dimension. The fractal dimension can reveal the nature attributes of electrical trees. Hence, the fractal dimension and the growth time of electrical trees can have close relationships.

The fractal dimension was deceasing while the moisture level and temperature were growing up. A final fractal dimension vs. tree growth time image was plotted to find the trend of them (Figure 14). In general, the fractal dimension of the electrical trees increases while the growth time goes down.

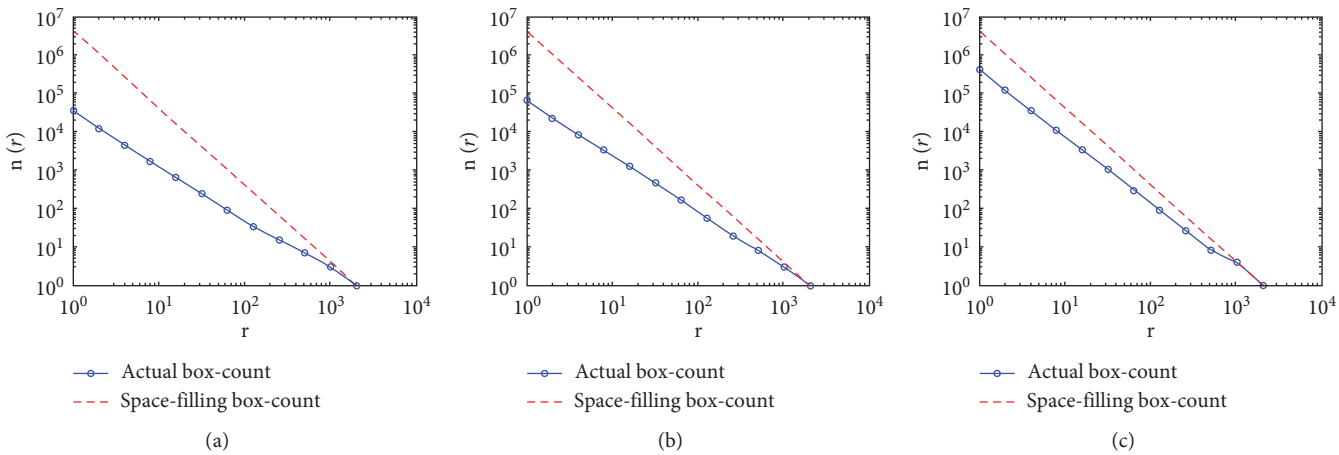


Figure 9: Fractal dimension distribution curve. (a) $D_f = 1.36$, (b) $D_f = 1.49$, (c) $D_f = 1.74$.

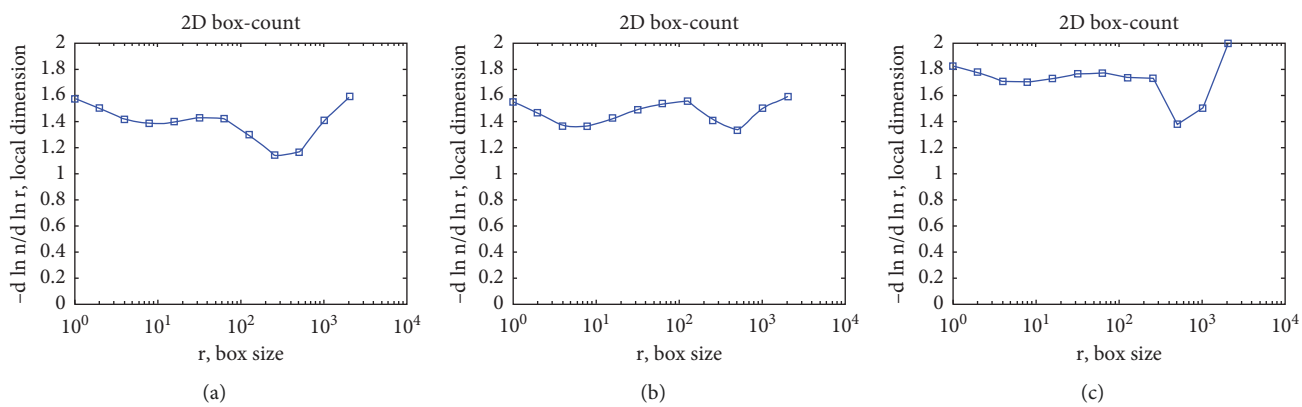


Figure 10: Local fractal dimension distribution curve. (a) $D_f = 1.36$, (b) $D_f = 1.49$, (c) $D_f = 1.74$.

Table 1: Tree growth at variable temperature of group A.

Sample	Moisture level	Temperature	Growth time	Fractal dimension
A1	0.03%	15°C	39 min	1.7332
A2	0.03%	20°C	20 min	1.6180
A3	0.03%	25°C	16 min	1.5739
A4	0.03%	30°C	7 min	1.4821

Table 2: Tree growth at variable temperature of group B.

Sample	Moisture level	Temperature	Growth time	Fractal dimension
B1	0.5%	15°C	28 min	1.6981
B2	0.5%	20°C	17 min	1.6271
B3	0.5%	25°C	9 min	1.5646
B4	0.5%	30°C	4.5 min	1.4767

Table 3: Tree growth at variable temperature of group C.

Sample	Moisture level	Temperature	Growth time	Fractal dimension
C1	1%	15°C	16 min	1.5739
C2	1%	20°C	8.5 min	1.5257
C3	1%	25°C	5 min	1.5002
C4	1%	30°C	3 min	1.4667

Table 4: Tree growth at variable temperature of group D.

Sample	Moisture level	Temperature	Growth time	Fractal dimension
D1	2.5%	15°C	12 min	1.5388
D2	2.5%	20°C	5 min	1.4981
D3	2.5%	25°C	2.5 min	1.2691
D4	2.5%	30°C	30 s break	Break

Figure 14 describes the relationship between the rate (growth time) and the extent (fractal dimension) of electrical tree growth affected by different environment conditions. As expected, the increasing rate of the fractal dimension drops while the growth time grows up. Although the general relation between the fractal dimension and growth time is not clear, the results also show the tree growth time and the fractal dimension of final electrical trees may trend synchronous changes at variable temperature and moisture level conditions. The final electrical tree can have similar fractal dimensions via similar tree growth time at different combinations of moisture level and temperature conditions. Temperature and absorbed moisture affect the rate and the extent of electrical tree growth time via the partial discharges. Similar partial discharge activity can lead to similar trees growth time

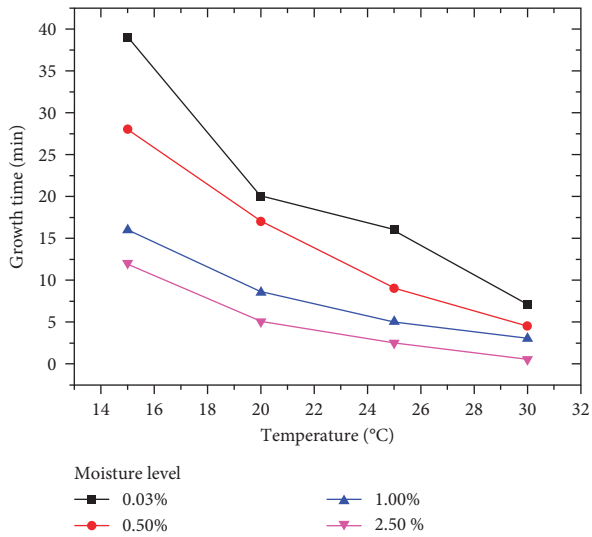


Figure 11: Growth time of electrical trees at different temperature and moisture.

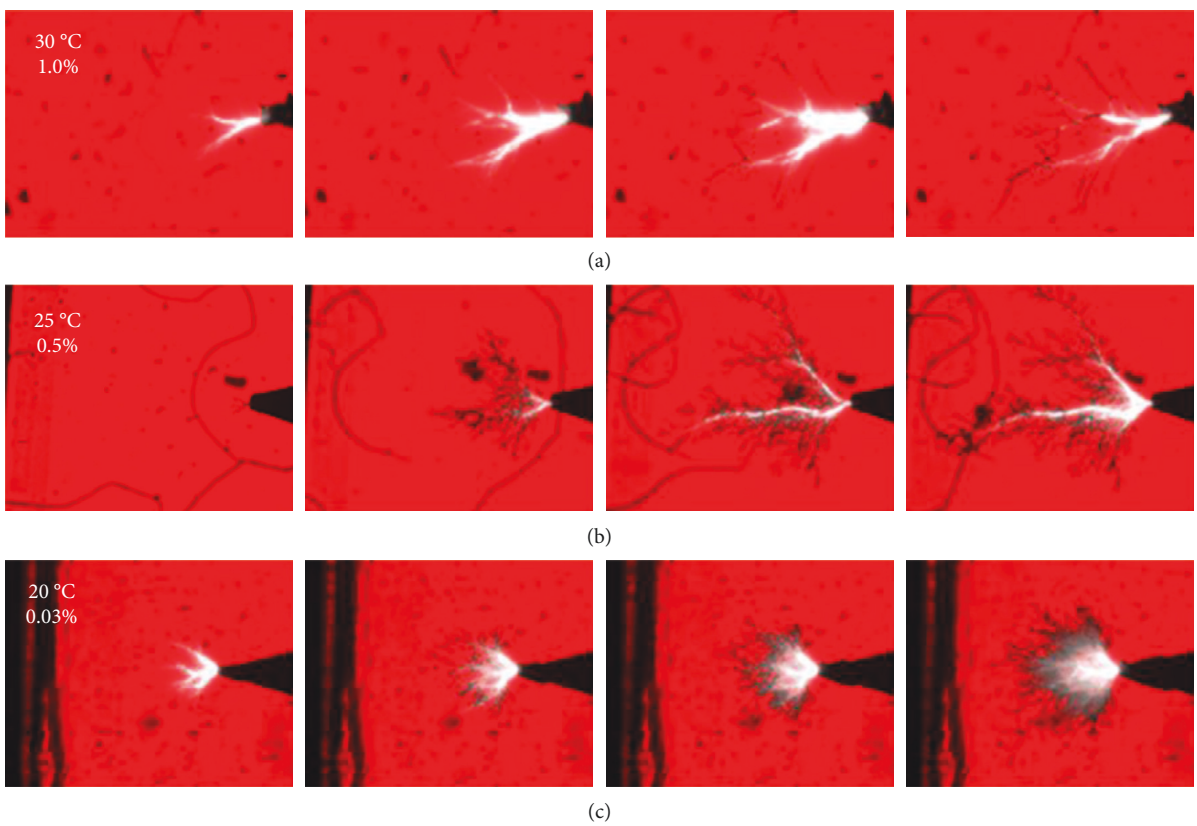


Figure 12: Superimposed red-white-black images of PD light and tree images with a same red and white light level: (a) a low-density tree with fast growth time, (b) a medium-density tree with medium growth time, (c) a high-density tree with slow growth time.

and trees growth extend. Same growth time trees could grow at different combinations of moisture level and temperature conditions. These different environment conditions combinations could lead to similar electrical trees fractal dimensions.

6. Conclusion

The aims of this paper were to study how the temperature and absorbed moisture affect the rate and the extent of electrical tree growth and estimate the extent of electrical

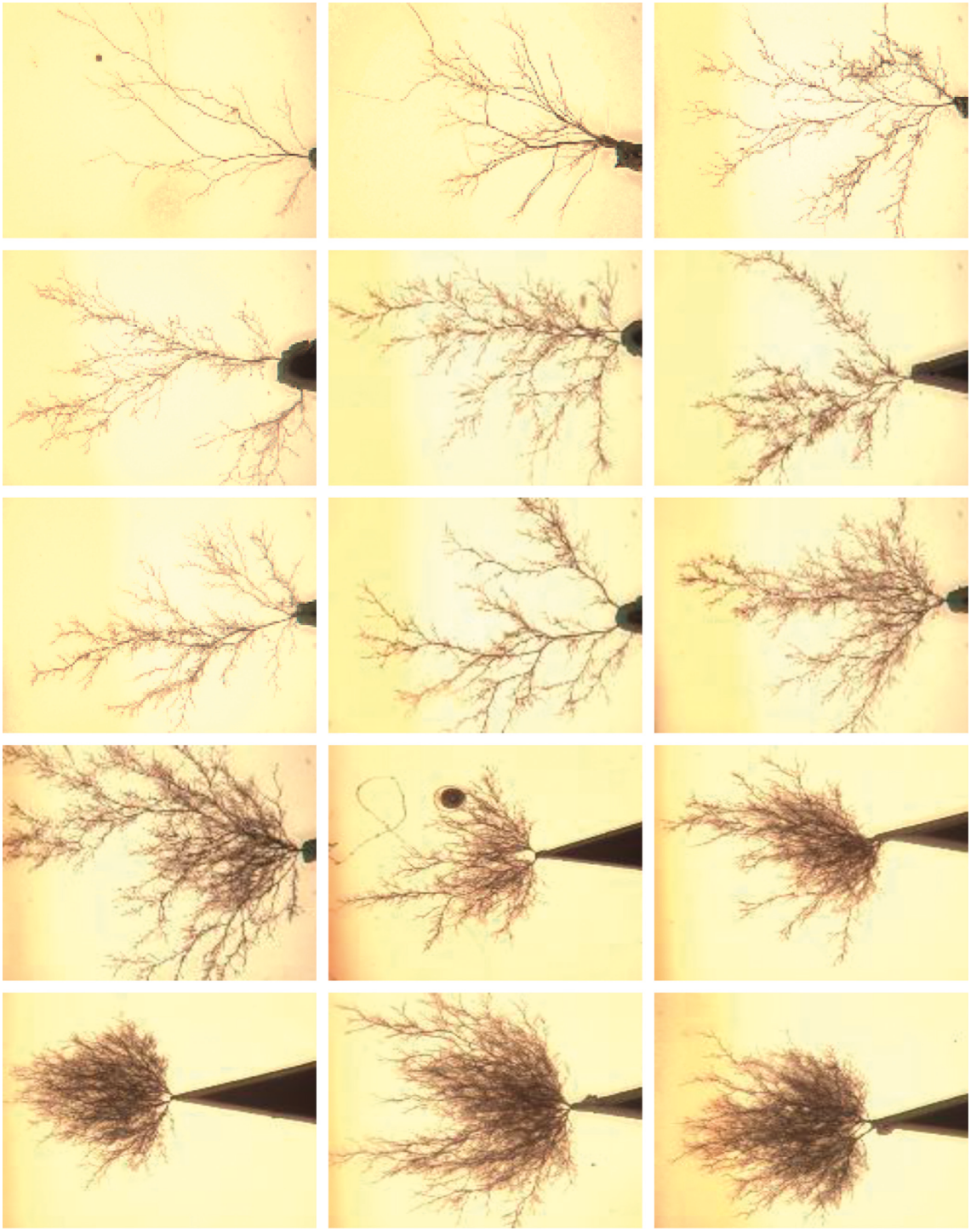


Figure 13: Superimposed images of final electrical trees.

tree growth using fractal dimension. The work has carried out a relationship between fractal dimension and growth time of electrical tree at different temperature and moisture level. The fractal dimension of the electrical trees decreases and the growth time goes up while the moisture level and temperature increases. Tree growth time and the fractal dimension of final electrical trees may trend synchronous changes at variable temperature and moisture level

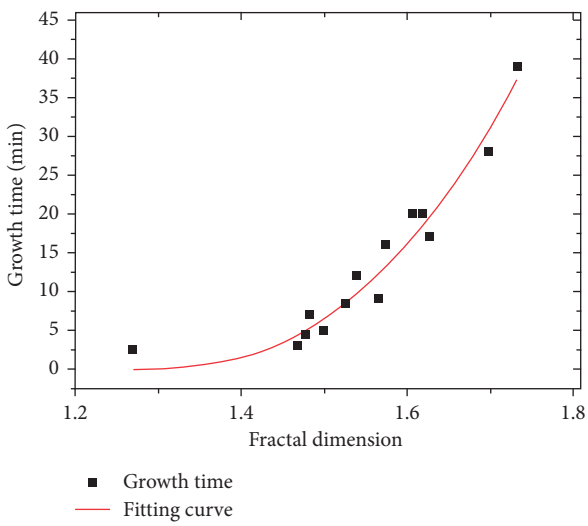


Figure 14: Fractal dimension vs. growth time.

conditions. On the basis of current study, further work build on this paper may imply improved methods to acquire 3-D electrical trees images.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare no conflicts of interest.

Authors' Contributions

Youping Fan proposed the project and supervised the paper. Dai Zhang wrote the Matlab codes, analysed the data, and drafted the manuscript. Jingjiao Li coordinated the study and helped to draft the manuscript.

Acknowledgments

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