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Hydrophobicity Classification of Polymeric Materials Based on Fractal Dimension

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This study proposes a new method to obtain hydrophobicity classification (HC) in high voltage polymer insulators. In the method mentioned, the HC was analyzed by fractal dimension (fd) and its processing time was evaluated having as a goal the application in mobile devices. Texture images were created from spraying solutions produced of mixtures of isopropyl alcohol and distilled water in proportions, which ranged from 0 to 100% volume of alcohol (%AIA). Based on these solutions, the contact angles of the drops were measured and the textures were used as patterns for fractal dimension calculations.

Keywords: *digital image, hydrophobicity, texture, fractal dimension*

1. Introduction

In the last decades, new polymeric materials such as silicone rubber, polyurethane and epoxy[1-3] have been used for high voltage outdoor insulation. The main characteristics of these materials are the low cost, easiness of molding, chemical stability and high resistance to natural conditions.

Among other characteristics, they also present low surface energy which can be explained by the presence of methyl groups on their surface. In fact, these materials are water-repellent, also called hydrophobic[4].

The hydrophobicity classification (HC) is defined by the STRI guide[5], by measuring the contact angle or the amount of the wetted insulator surface. This method, generally used in the field has an intrinsic inaccuracy due to its subjective image analyses.

About 30 years ago, mathematicians as Von Kock, Peano, Hausdorff, Besicovitch and others ones created pictures which were called "monsters" or "pathologic" by some others mathematicians[6] because these pictures were created by fractal geometry calculations. Recently, the fractal geometry has been applied in digital image processing methods to image-file compression[7], segmentation techniques[8], surface roughness characterizations in fractures[9], wear and erosion surfaces[10].

Some researchers have proposed digital image analyses to classify the hydrophobicity of the electrical insulators. Circular factor[11,12], goniometric measurement using Hough transformation[13], segmentation, scaled entropy and histogram analyses[14] and surface energy[15] were some of the proposed methods, but neither of them were able to obtain a mathematical relationship which may define HC. This paper presents a new approach where this HC identification is possible using the fractal dimension as a parameter to quantify the texture of the images and classify the HC.

2. Experimental Procedure

The material employed in the experiment procedure was silicon rubber outdoor insulators. Ten specimen were cut out from each sheet, each one with (10 x 10) cm^2 and 5 mm thickness. The solutions of water and isopropyl alcohol (%AIA solution) were sprayed on samples, which ranged from 0 to 100% volume in alcohol. In this way, discrete texture images were obtained (%AIA image), providing a possibility of comparison and classification according to the STRI Guide.

At first, ten grayscale VGA images from each solution of the drops and the surfaces (OR) were taken and the contact angles were measured. In order to avoid differences or gradients in the illumination, caused by natural conditions, the original images were modified by histogram equalization (EQU) and/or white top-hat filter (WTH). The EQU promotes the balance in the grayscale distribution; in other words, all range of the grayscale is presented in the image. Another way to suppress the conditions of illumination is the edge detection tool, which produces images with the drop patterns, with the Sobel operator (SOB)[16] being used in this case. The contact angle was measured from the drops with the aid of a CAD software.

The WTH works as a high-pass filter, reducing the gradient illumination of an image normally obtained in natural conditions. In order to apply the WTH filter, the opening image should be initially defined from Equation 1:

$$\gamma_B(f) = \delta_B[\varepsilon_B(f)] \tag{1}$$

where δ_B is the dilatation and ε_B is the erosion of an f image.

Equation 2 presents the mathematical operator of the WTH. In order to define the best opening size for WTH images, the opening mask size (*B*) has been changed from 3 x 3 to 121 x 121 pixels, and convergence was analyzed. This procedure was taken to reduce the computer processing time.

$$\mathrm{WTH}(f) = f - \gamma_B(f) \tag{2}$$

2.1. Fractal dimension

The fractal dimension calculations have been performed by the box-count method in the grayscale images[17], with the box-size ranging

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from 3 to 11. The fractal dimension based on the box-count method can be defined by:

$$D_n = \frac{\log N_n}{\log 2^n} \quad (3)$$

where the linear fitting of D_n for many *n* values presents the fractal dimension (df) of an image divided *n* times and N_n is the number of boxes crossing the image.

The N_n calculation can be obtained based on grayscale values from pixels grid (i,j) as it follows:

$$N_n = \sum n_n(i,j) \quad (4)$$

The n_n values are obtained from the equation 5, where:

$$n_n(i,j) = \sum \frac{Gray_{\max}(i,j) - Gray_{\min}(i,j)}{S'} + 1 \quad (5)$$

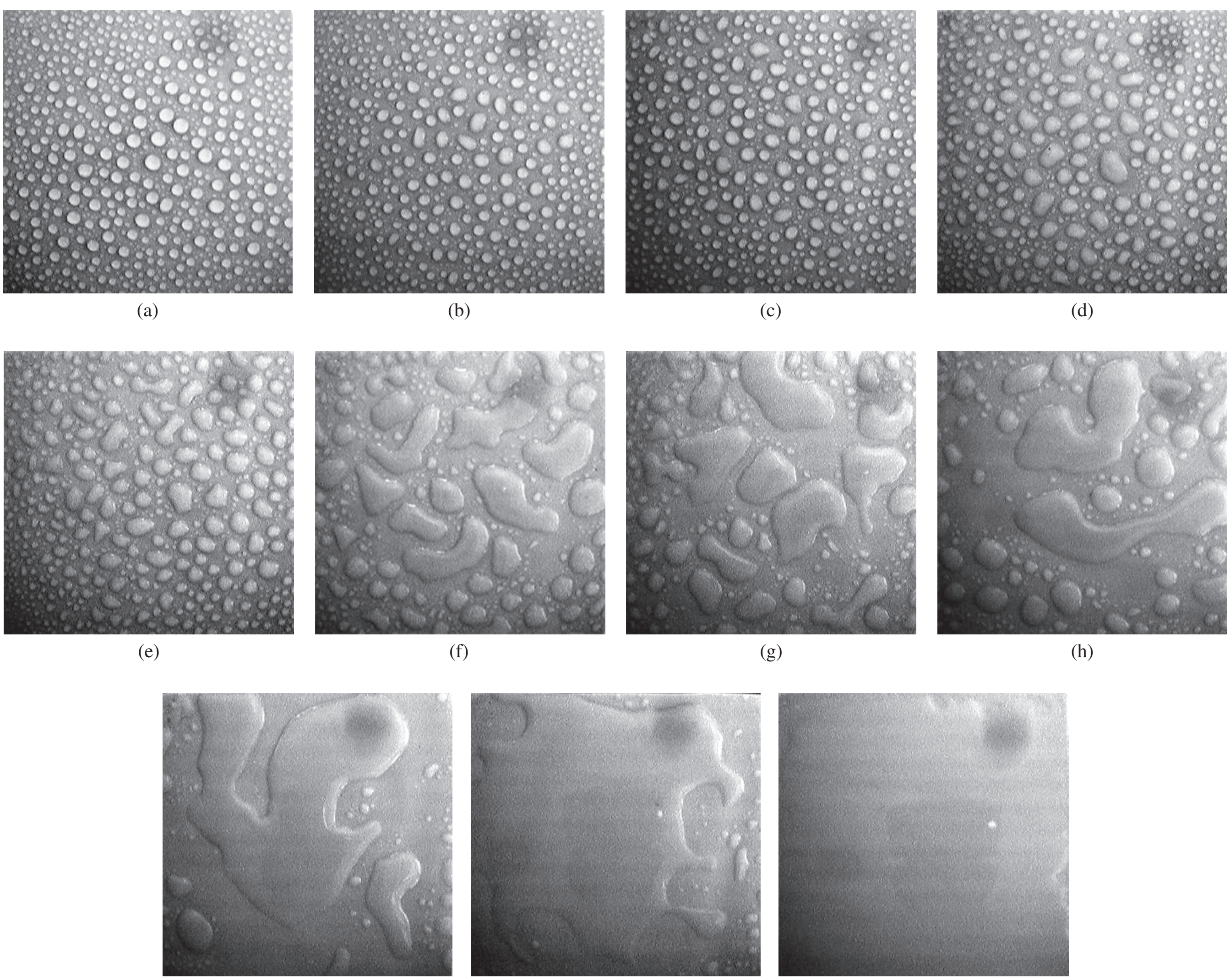
where $Gray_{max}$(i,j) and $Gray_{min}$(i,j) are the maximum and minimum grayscale image values in the grid (i,j) and S' is the size of the box.

In this way, N_n is taken for different values of n, that is, from different sizes of grids. This way of counting leads to a better approximation of the boxes that intercept the surface of the grayscale levels in the image. The df is obtained from the average value of D_n, or the angular coefficient of the linear fit from n vs. D_n dilog plot.

3. Results and Discussion

Figure 1 shows pictures of surfaces, in which each one of them was sprayed with %AIA solution. It was possible to observe a discrete evolution from hydrophobic to hydrophilic behavior, where the shape of the drops changes from circular to a water film, passing through irregular shapes, and the increase in the amount of the wetted surface.

In the pictures presented in the Figure 1, it is possible to observe the changing in the texture of the images. As the contact angle increases, the wetted area also increases. Another observed behavior was the decreasing in the circular factor of the drops with the addition of alcohol; this situation can be attributed to the low homogeneity of the surface[18].



(a) (b) (c) (d) (e) (f) (g) (h) (i) (j) (k)

Figure 1. Original images from surfaces sprayed with solutions of a) 0 to k) 100 %AIA solutions.

Differences in the illumination could also be observed in the Figure 1. Based on this, EQU and/or WTH filter should be applied to reduce these illumination gradients. In order to compare these images with the STRI classification, the contact angles were measured as a function of the %AIA solution, thus, the HC was related to each one (see Figure 2), until the HC03. According to the STRI Guide, for an HC level above 04, the value must be defined using not only the contact angle, but also the amount of the wetted surface, which can be observed in the Figure 2. The mathematical fit was performed based on a third degree polynomial function, only for future comparisons between the contact angle and the image texture.

In order to define the opening image to be used as the WTH filter, the behavior of the volume of these images, i.e. the sum of all pixel values in the image, as a function of *B* (see Figure 3) was performed. The derivate curve begins to converge in $B = 41 \times 41$ indicating that *B* values above 41×41 will not produce higher changes in the image. Thus, this value was adopted to reduce the processing time for each image.

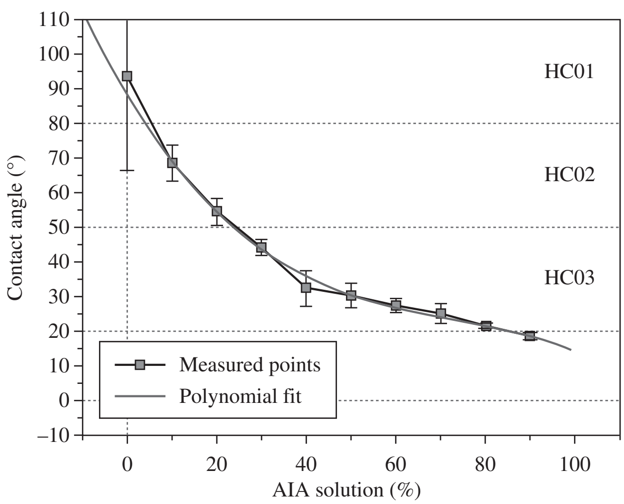


Figure 2. %AIA solution vs. contact angle.

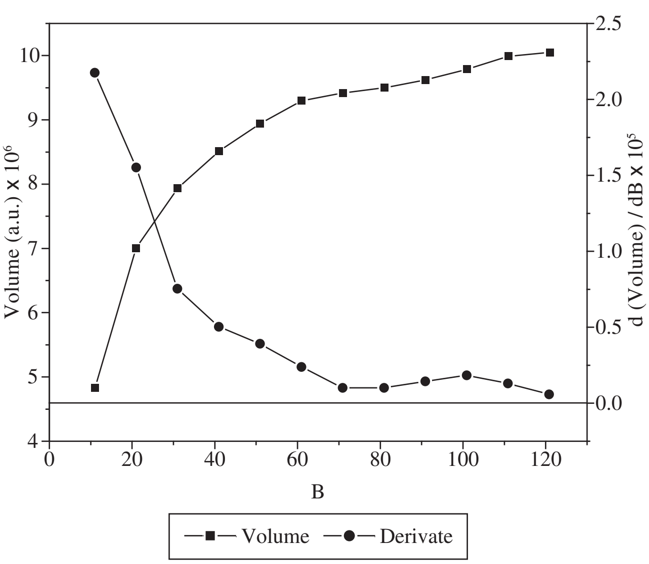


Figure 3. Opening images volume and its derivate as a function of B.

As it follows, it can be observed in the Figure 4a, the opening image process obtained from the original Figure 1a with $B = 41 \times 41$. As the image has one area clearer than the other, this part is more visible in this image. If the original image had the same illumination as the previous one, the opening image should have been completely dark. Figure 4b shows the final result obtained after the WTH operation, where it can be noticed that the variation in the illumination was significantly reduced, showing the efficiency of this method then.

Figure 5 presents the a) OR, b) EQU, c) WTH, d) EQU+WTH, e) EQU+WTH+EQU and f) SOB images, showing artificial illumination adjustments produced in each sample of image.

The fractal dimension of these images has been calculated based on Equation 3 and the results are plotted in the Figure 6. It can be observed that dispersion in the results, in general, are around 3% and all the curves tend to converge. As the main goal of this study is to predict the behavior of the hydrophobicity in polymeric surfaces, an injective function was sought in order to provide a reliable mathematical identity.

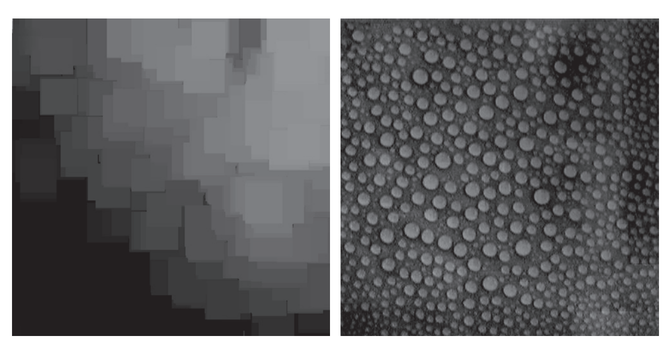
As a result, this injective function between %AIA image and *df* could only be obtained from the WTH images, with its equation being as it follows:

$$\%AIA = 97.0207 \times \exp\left(\frac{2.4394 - df}{0.08067}\right) \tag{6}$$

The Equation 6 relates the image texture from the patterns based on %AIA images and its fractal dimension value. In other words, this method provides a direct quantification of the hydrophobicity due to its texture characteristics. The main advantage of it is the objective classification promoted by this method, avoiding the subjective analysis of the operator.

4. Conclusions

A new method to relate the hydrophobicity classification according to STRI is proposed based on the digital image processing. Several samples of the image textures have been produced by spraying water-isopropyl alcohol solutions on polymer surfaces. In order to avoid the gradient of illumination of the pictures taken under natural conditions, different procedures as histogram equalization, white top-hat filter and edge detection have been tested. By using the fractal dimension to analyze the textures of the polymeric wetted surface images, it was possible to determine a mathematical function that can classify the hydrophobicity of the polymeric surfaces by digital image analyses.



(a) (b)

Figure 4. a) WTH filter and b) WTH Image of a 0% AIA image.

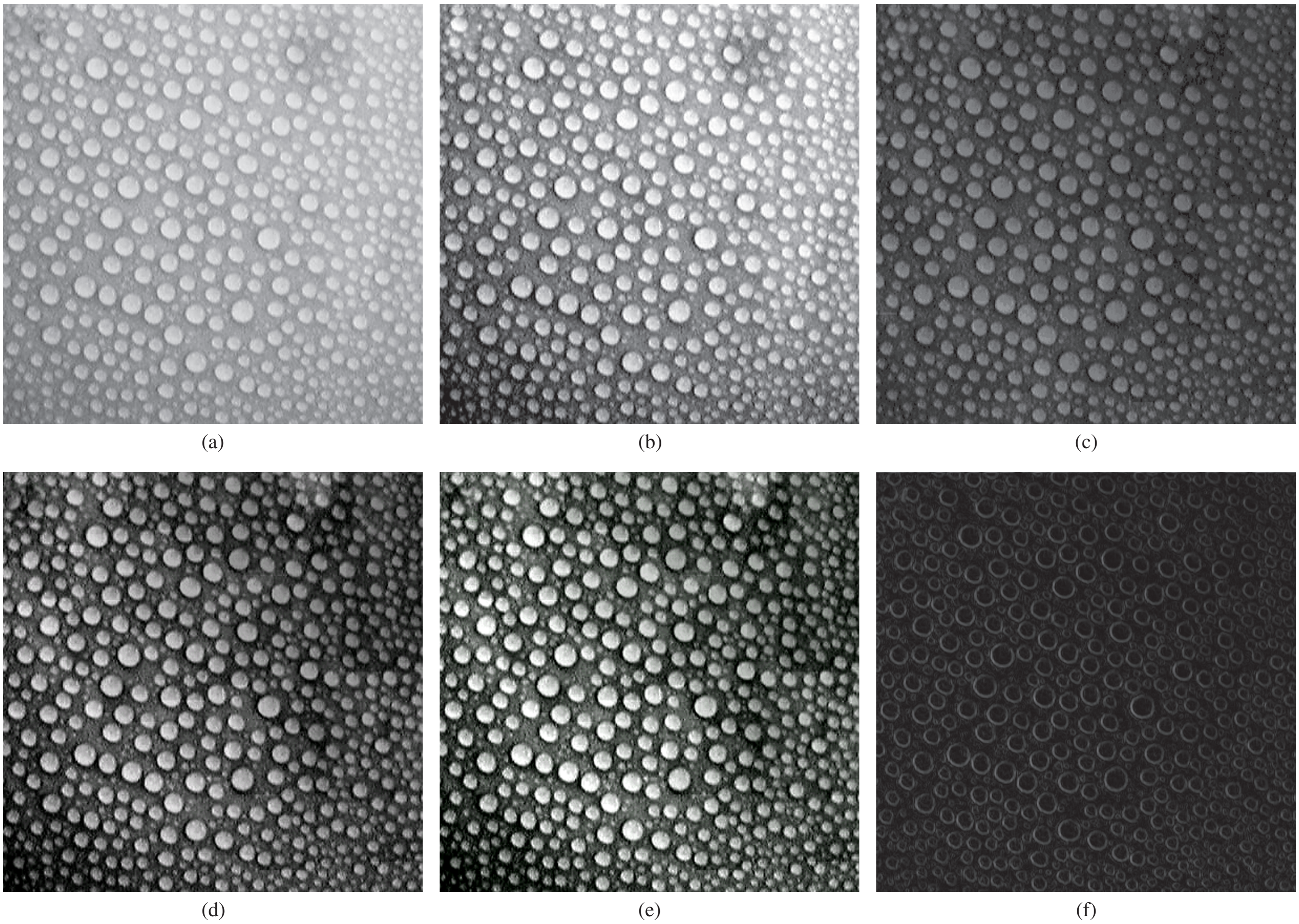


Figure 5. Images produced by various models of illumination adjustments: a) OR, b) EQU, c) WTH, d) EQU+WTH, e) EQU+WTH+EQU and f) SOB images.

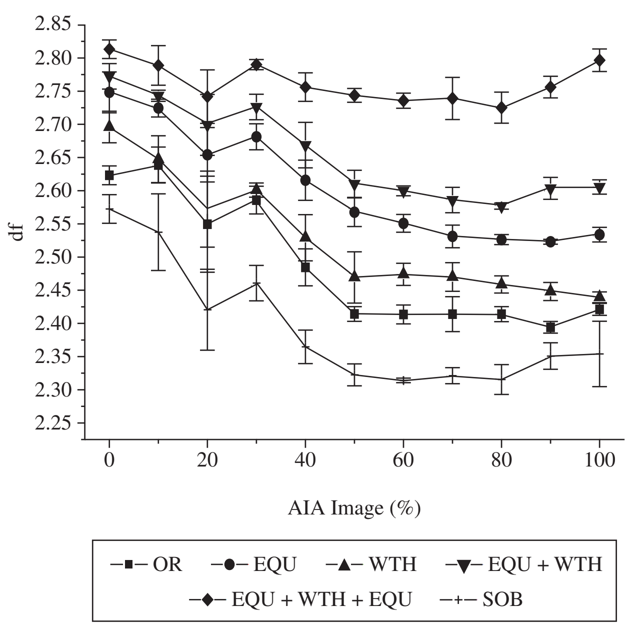


Figure 6. *df* values of various %AIA images.

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