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A Non-Destructive Optical Method for the DP Measurement of Paper Insulation Based on the Free Fibers in Transformer Oil

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Abstract: In order to explore a non-destructive method for measuring the polymerization degree (DP) of paper insulation in transformer, a new method that based on the optical properties of free fiber particles in transformer oil was studied. The chromatic dispersion images of fibers with different aging degree were obtained by polarizing microscope, and the eigenvalues (*r*, *b*, and Mahalanobis distance) of the images were extracted by the RGB (red, blue, and green) tricolor analysis method. Then, the correlation between the three eigenvalues and DP of paper insulation were simulated respectively. The results showed that the color of images changed from blue-purple to orange-yellow gradually with the increase of aging degree. For the three eigenvalues, the relationship between Mahalanobis distance and DP had the best goodness of fit (R^2 = 0.98), higher than that of *r* (0.94) and *b* (0.94). The mean square error of the relationship between Mahalanobis distance and DP (52.17) was also significantly lower than that of *r* and *b* (97.58, 98.05). Therefore, the DP of unknown paper insulation could be calculated by the simulated relationship of Mahalanobis distance and DP.

Keywords: degree of polymerization; free FIBER; paper insulation; chromatic dispersion image; RGB tri-color analysis

1. Introduction

At present, the majority of transformers in power systems are oil-immersed transformers. The service life of oil-immersed transformers depends mainly on the solid insulation (paper insulation), which can be evaluated by the average DP of the paper insulation [1–3]. In the practical operating environment, the aging degree of paper insulation in transformers was mainly obtained by the indirect detection methods of dissolved CO/CO_2, methanol, and furfural content in oil [4–6]. However, the disadvantages of the indirect detection methods are poor accuracy of measuring equipment and interference of filtering operation, which may lead to misjudgments [7]. The other kind of measuring method is the direct method which is the measurements of DP or tensile strength of paper insulation [8]. However, the direct method is a kind of destructive testing method and needs inconvenient operations to get paper samples, leading to operational obstacles and less application in practical measurements [9–11].

In recent years, some Japanese scholars show that the fibers suspended in transformer oil come from the aged paper insulation directly, and the related characteristics of fibers can reflect the aging degree of the paper insulation. It is proposed that the aging degree of paper insulation can be evaluated according to the optical characteristics of the fibers in oil [11,12]. Since this method is almost unaffected by filtering and change of transformer oil and can be used for on-the-spot measurement of transformers in operation, it has attracted wide attention [13,14]. However, it is difficult to quantify the optical characteristics of the fiber particles. In this paper, based on the different colors of fiber images, the color eigenvalues of images were extracted by the RGB tricolor analysis method, and the color eigenvalues were related to the DP of paper insulation. Therefore, the aging degree of paper insulation could be evaluated by the optical characteristics of the fiber particles in transformer oil.

2. Principle

The increase of the aging degree of insulation papers is accompanied by the increase of refractive index of fibers in the oil [14] and the color change of the fiber dispersion images. When the fiber dispersion images are obtained, the color characteristics of different aging degree fibers are extracted to evaluate the aging condition of paper insulation.

Chromatic dispersion monitoring method [15] is a commonly used method for the detection of refractive index of tiny solid particles like fibers. When using this method, the fiber particles should be immersed in a given refractive index matching solution to make samples, and then white light is used to irradiate the measured particles vertically. When the white light passes through the interface between the fiber edge and the matching liquid, each frequency in white light is divided into two transmitted lights due to the birefringence of fibers, which are defined as α and γ light ($n_\alpha < n_\gamma$), respectively. As known, the transmitted light of different frequencies (α or γ) occur different degrees of deflection, that is, the dispersion effect. The dispersion curves of the fibers and the matching solution are shown in Figure 1. In Figure 1a, the two dispersion curves of fibers and the dispersion curve of the matching liquid intersect at λ_1 and λ_2 respectively, where λ_1 and λ_2 are defined as matching wavelengths.

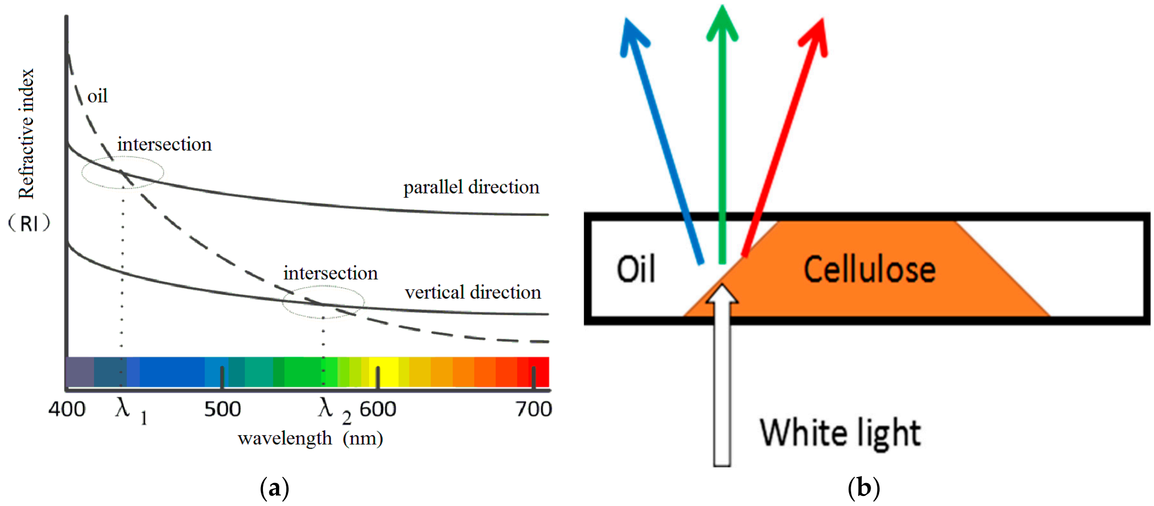


Figure 1. (**a**) Matching wavelength diagram; (**b**) dispersion of fiber.

For α light, it can be divided into three parts according to the refractive characteristics. When $\lambda < \lambda_1$, the refractive index of the matching solution is higher than that of fibers, which means the transmitted light will be deflected towards the oil direction (blue light in Figure 1b according to Snell's law; When $\lambda > \lambda_1$, the refractive index of the matching solution is lower than that of fibers, which means the transmitted light will be deflected towards the fibers direction (red light in Figure 1b); When $\lambda = \lambda_1$, the transmitted light will maintain the original direction (green light in Figure 1b). Similarly, the same is true for the γ light.

The refracted light from the interface between the fibers and matching liquid disperses in the objective lens and then appears in the images. The color of images corresponds to the refractive index of fibers. If a polarized light source is used and the polarization direction is parallel or perpendicular to the fibers, the transmitted light will contain only α and γ light and the dispersion color will be only related to λ_1 or λ_2.

3. Results and Discussion

3.1. Size Distribution of Fiber Particles at Different Aging Degrees

In this work, the DP measurement of paper insulation was based on the characteristics of free fiber particles in oil, so the particle size with different aging degrees was monitored firstly. The fiber particles that aged at 130 °C for 0, 4, 7, 10, 22, 35, 60, and 90 days in a given volume of oil were measured by a granularity measuring instrument. When the particle numbers of oil samples were measured, five identical volumes of oil samples were tested simultaneously, and the average values were obtained. The results were shown in Figure 2.

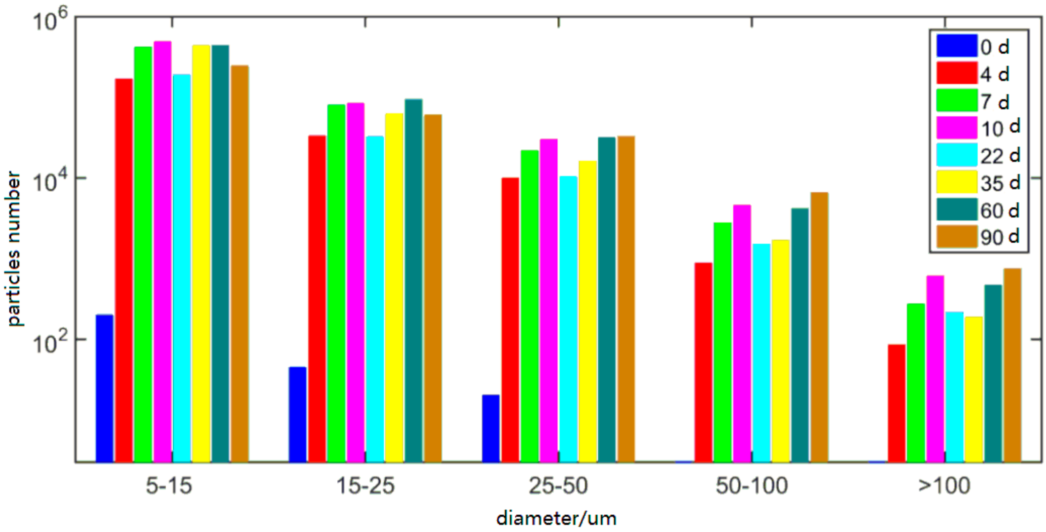


Figure 2. Particle size distribution of fibers in oil with different aging days at 130 °C.

As shown in Figure 2, the amount of aged fiber particles (red, green, purple, etc. in Figure 2) was much higher than that of original one (blue in Figure 2), which meant the fiber particles fell into oil as the paper insulation aged. The diameter of the free fibers concentrated in the range of 5–50 μm mainly, with small particles (5–15 μm) as the main component. However, with the increase of aging time, the size of particles in each range did not change obviously.

3.2. Morphology of Fibers at Different Aging Degrees

In order to explore the aging degree of fibers in different environments, the fibers morphology at 130 °C for different aging time (0, 4, 7, 10, 22, 35, 60, and 90 days) was observed. The samples for the aging experiments are all the same type and from the sample company. Moreover, the samples are all the same sizes and the observation points are the central location of the samples. The results were shown in Figure 3.

From Figure 3, it could be seen that the fibers began to break, and cracks or holes appeared on the surface with time. In the early stage of aging (from the beginning to the aging of 10 days), the topography of fibers changed little (no obvious gaps and holes appeared), but obvious cracks and holes began to appear in the middle stage of aging (from 35 to 60 days). In the later stage (from 60 to 90 days), visible signs of breakage could be observed clearly. These three aging processes showed that the properties of fibers were deteriorating as the aging degree increased, which would affect the DP of fibers [16,17].

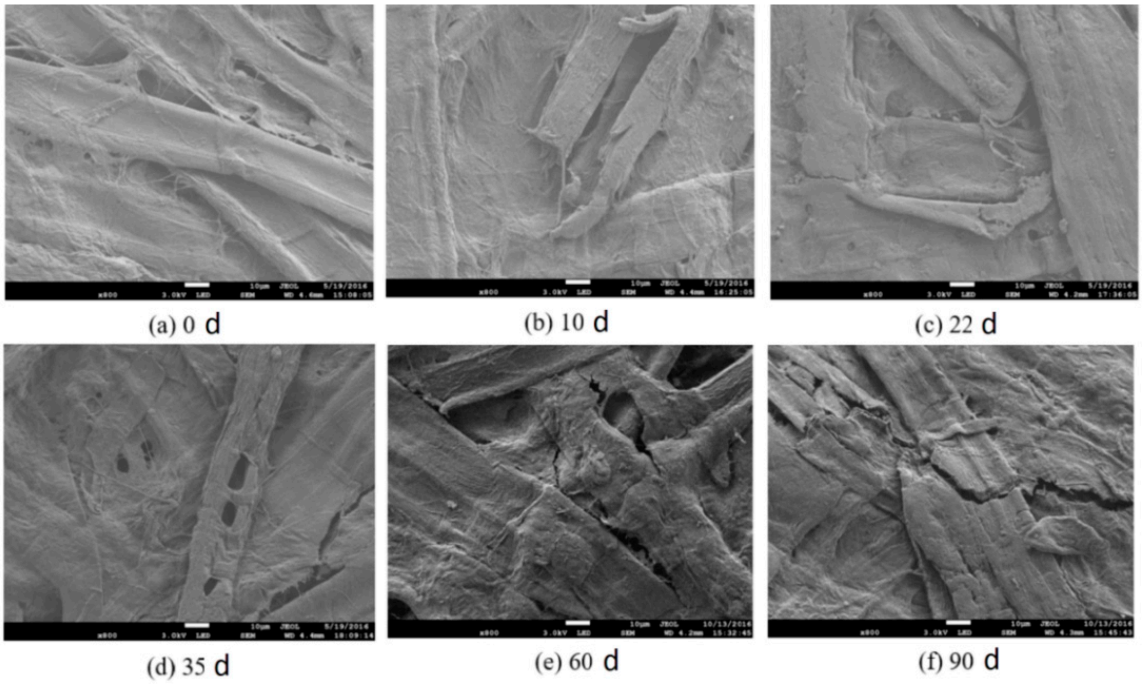


Figure 3. Fiber morphology at different aging times.

3.3. Dispersion Images of Fibers with Different Aging Degrees

The chromatic dispersion images of fiber particles in different aging time were obtained by polarizing microscope. Figure 4 showed the dispersion color of fibers in oil with different aging days at 130 °C. It can be seen from Figure 4 that the fibers showed blue at the beginning of aging; as the aging days increase, the blue color of images reduced gradually, and then, yellow, red, and orange appeared; in the late aging stage, the images exhibited mostly yellow or red. The trend of color change with aging time was the same as Masanobu Yoshida described in his research [14].

As reported by results of the study of Masanobu Yoshida [14], the blue color indicated that the refractive index of the fiber particles was low, and the intersection of fibers and matching liquid was located in a high wavelength band. The red or yellow color indicated that the refractive index of the fiber particles was high, and the intersection of fibers and matching liquid was located in a low wavelength band. Therefore, the changed color of chromatic dispersion images could be used to reflect the change of refractive index and DP of the paper insulation.

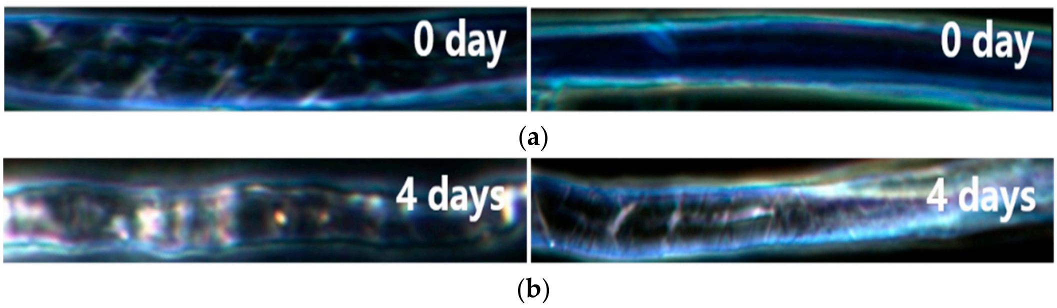


Figure 4. *Cont.*

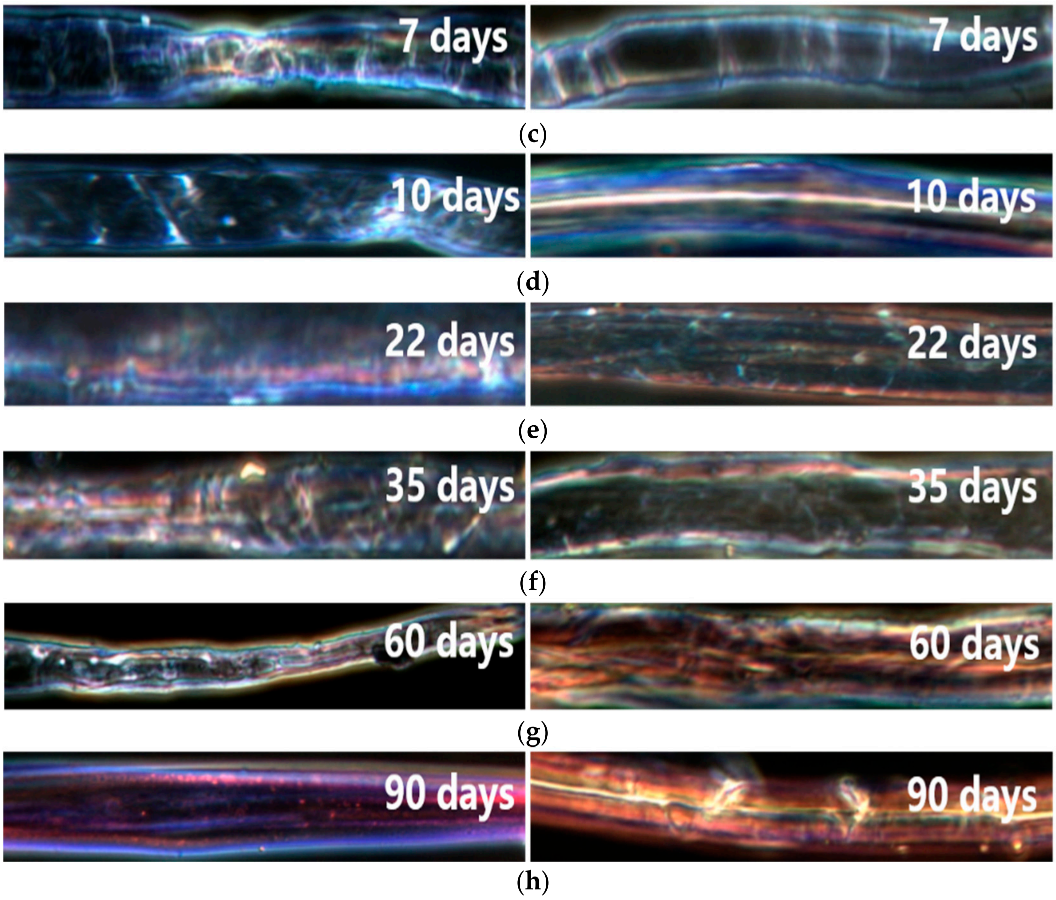


Figure 4. Typical chromatic dispersion color of fibers in oil at different aging stages. (**a**) 0 days for aging; (**b**) 4 days for aging; (**c**) 7 days for aging; (**d**) 10 days for aging; (**e**) 22 days for aging; (**f**) 35 days for aging; (**g**) 60 days for aging; (**h**) 90 days for aging.

3.4. Analysis of Chromatic Dispersion Images

In order to quantify the color of chromatic dispersion images of fiber particles with different aging degrees, the color eigenvalues of images were extracted from the characteristic regions by the RGB tricolor analysis method [18]. Inspired by the research of Masanobu Yoshida and Yoshinori Konishi [14], the color of images was firstly restored to three primary colors (red, blue, and green) by the MATLAB software (2016a, MathWorks, Natick, MA, USA), and then, the colors were defined as Equation (1) according to the RGB values

$$\begin{cases} r = \frac{1}{p}\sum\limits_{j=1}^{p}\frac{R_j}{R_j+G_j+B_j} \\ b = \frac{1}{p}\sum\limits_{j=1}^{p}\frac{B_j}{R_j+G_j+B_j} \end{cases} \tag{1}$$

In Equation (1), R, G, and B are the values of red, green, and blue of the images respectively, which range from 0 to 255; j = 1, 2, 3, ..., p, and p are the number of effective pixels of the images; r is the ratio of the red component of image, b is the ratio of the blue component of image.

The color eigenvalues of r and b were obtained by Equation (1), and then, scatter plots were made in Figure 5.

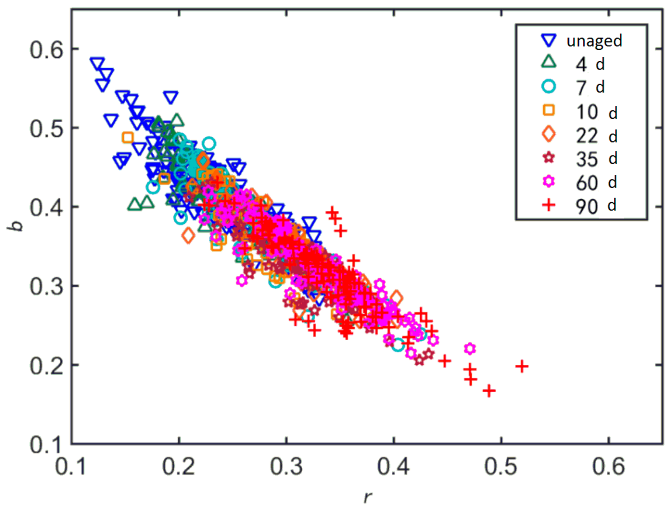


Figure 5. r, b values of chromatic dispersion images for fibers under different aging stages.

As shown in Figure 5, the fibers had a higher proportion of blue component b at the beginning of aging, and then the red component ratio r gradually increased as the aging time increased, that was, the scatter plots (r, b) moved to the lower right with the aging time. According to this feature of scatter plots, an eigenvalue from r and b was extracted to reflect the aging degree of paper insulation.

3.5. Eigenvalue Extraction of Chromatic Dispersion Images

As the (r, b) values of chromatic dispersion images had special regularity with the increase of aging time, the r, b and their coupling eigenvalue were extracted from Figure 5, and then these three eigenvalues were fitted with the DP of paper insulation to obtain linear relationships. In this work, the coupling eigenvalue of r and b was extracted by Mahalanobis distance method [19,20]. Mahalanobis distance was defined as Equation (2)

$$d = \sqrt{(\boldsymbol{y} - \boldsymbol{\mu})^T \boldsymbol{S}^{-1} (\boldsymbol{y} - \boldsymbol{\mu})} \tag{2}$$

where, y = $(y_1, y_2, \ldots, y_m)^T$ is a column vector with m-dimensional variables; $\mu = (\mu_1, \mu_2, \ldots, \mu_m)^T$ represents a particular distribution that contains m-dimensional variables; $\mu_1, \mu_2, \ldots, \mu_m$ are each variable, and S is covariance. In the study, the Mahalanobis distance d_i is shown in Equation (3)

$$d_i = \sqrt{(\boldsymbol{y}_i - \boldsymbol{\mu}_0)^T \boldsymbol{S}_0^{-1} (\boldsymbol{y}_i - \boldsymbol{\mu}_0)} \tag{3}$$

where, $y_{\mathrm{i}} = (r_i, b_i)^T$ is the vector of r and b for the ith observation (ith feature area) in each chromatic dispersion image; $\mu_0 = (r_0, b_0)^T$ is the vector of r and b for image of unaged fibers.

The Mahalanobis distance that based on the three primary color ratio was defined as the eigenvalue (PCR-MD, referred as D), and D could be obtained from Equation (4)

$$D = \frac{1}{n} \sum_{i=1}^{n} d_i \tag{4}$$

At the same time, the relationship between furfural concentration in oil and DP of paper was also compared. When the data were collected and simulated to form linear charts, it was found that semi-log axes could have better linear relationship than other axes. So, the simulated relationship between r, b, and D were used the semi-log axes. The results were shown in Figure 6a–d.

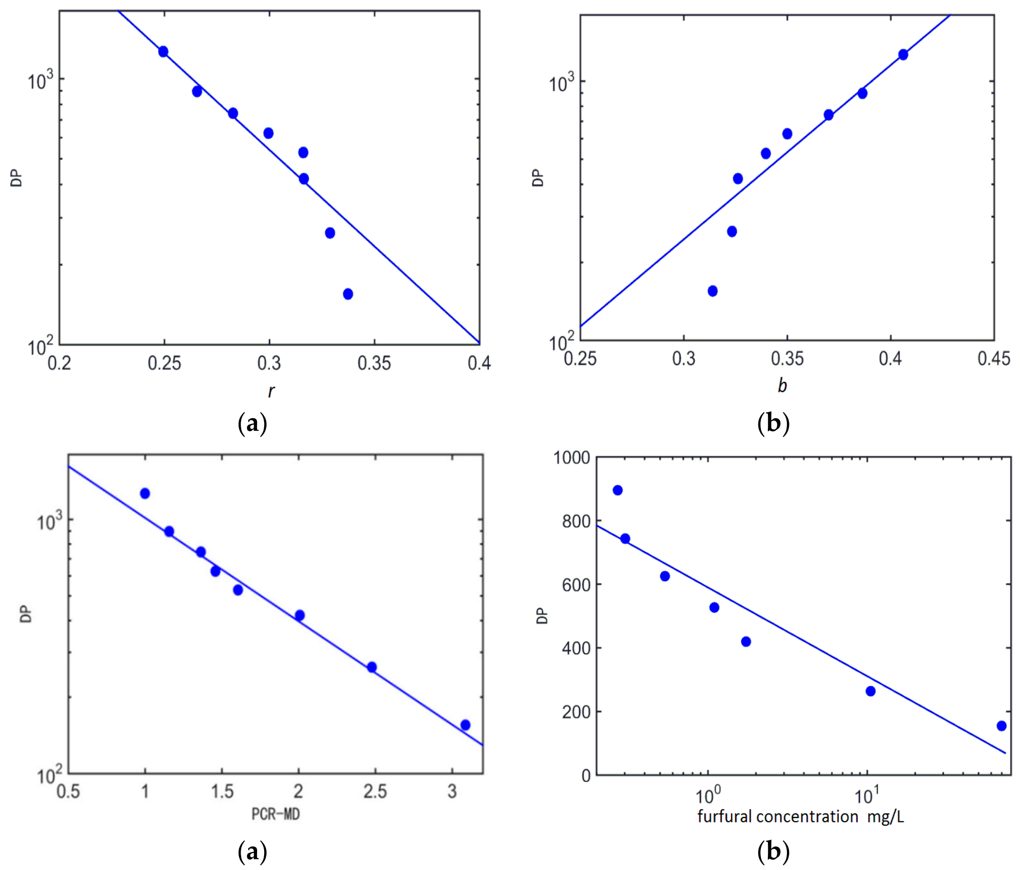


Figure 6. (**a**) Fitting of DP and r; (**b**) Fitting of DP and b; (**c**) Fitting of DP and D; (**d**) Fitting of DP and furfural concentration.

From Figure 6a–d, the fitting results of DP and four parameters showed that the linear relationship between PCR-MD and DP was significantly better than that of *r*, *b* and furfural with DP. To quantify the fitting effect, the fitting parameters (k_1, k_2, k_3, and k_4), goodness of fit (R^2) and mean square error (RMSE) were compared, which were shown in Table 1.

Table 1. Comparison of fitting parameters (k_1, k_2, k_3, and k_4), goodness of fit (R^2), and mean square error (RMSE)

Parameters	k_1	k_2	k_3	k_4	R^2	RMSE
r	80910	−7.25	-	-	0.94	97.58
b	2.37	6.72	-	-	0.94	98.05
PCR-MD	2586	−0.41	-	-	0.98	52.17
Furfural concentration	-	-	589.7	−278	0.89	95.10

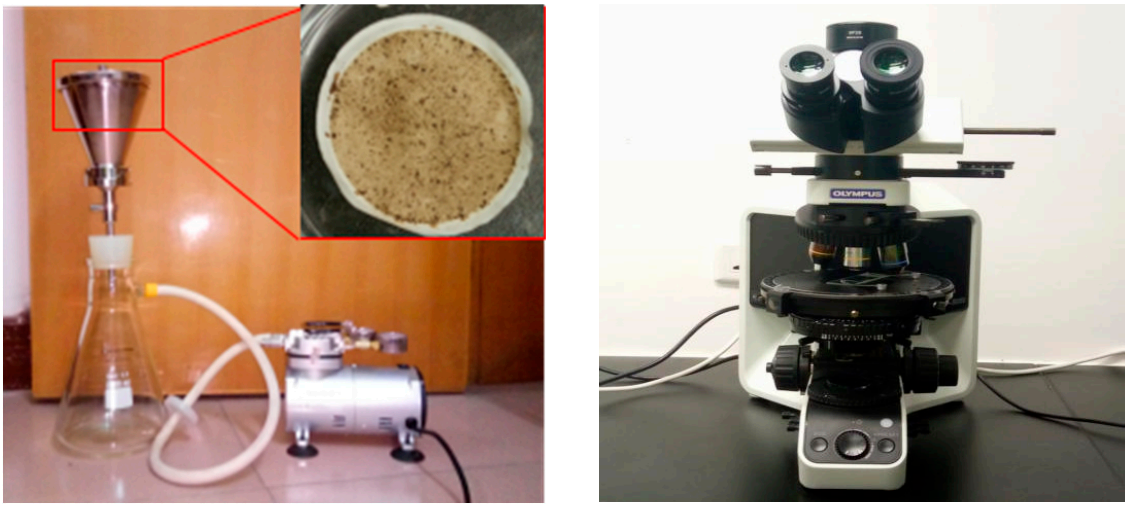
From Table 1, the goodness of fit (R^2) of PCR-MD was 0.98, which was higher than that of *r* (0.94), *b* (0.94), and furfural concentration (0.89). The mean square error of PCR-MD was 52.17, lower than that of *r* (97.58), *b* (98.05), and furfural (95.10) significantly, indicating that PCR-MD could describe the relationship between DP and the optical properties of fibers more accurately than that of *r*, *b*, and furfural. The relationship was shown in Equation (5)

$$DP = 2586 \times 10^{-0.41D} \quad (5)$$

4. Test Methods

(1) Extraction of fiber particles in oil: Paper insulation was immersed in transformer oil and then aged for 0, 4, 7, 10, 22, 35, 60, and 90 days at 130 °C. Filtration device was used to extract free fiber particles from the transformer oil. The diameter of membrane used in this work was 1 µm, and the filtration device was shown in Figure 7a.

(2) Analysis of dispersion images: When free fiber particles was obtained, the polarizing microscope was used to get the dispersion images, as shown in Figure 7b. Then the MATLAB software was used to analyze the dispersion images by RGB tricolor analysis method.



(**a**) (**b**)

Figure 7. (**a**) Experimental filter device; (**b**) polarizing microscope.

5. Conclusions

In this paper, a non-destructive method for measuring the DP of paper insulation in transformer was proposed, which was based on the chromatic dispersion images of free fiber particles in transformer oil. Three eigenvalues (r, b, and Mahalanobis distance) of the images were extracted by the RGB tricolor analysis method. It was found that the color of images changed from blue-purple to orange-yellow gradually with the increase of aging degree. The relationship between Mahalanobis distance and DP had the best goodness of fit (R^2 = 0.98), higher than that of r (0.94) and b (0.94). The mean square error of the relationship between Mahalanobis distance and DP (52.17) was also significantly lower than that of r and b (97.58, 98.05).

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Author Contributions: Lei Peng and Qiang Fu conceived and designed, performed the experiments, and analyzed the data; Yaohong Zhao, Yihua Qian, Tiansheng Chen, and Shengping Fan contributed materials analysis; Lei Peng wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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