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Diagnosis for Aging Degradation of Insulating Paper in Power Transformers by Measuring the Refractive Index of Cellulose Fibers

Masanobu Yoshida and Yoshinori Konishi, *non-Members, IEEE*

***Abstract*— This paper proposes a new diagnosis method for aging degradation of insulating paper in power transformer. We took note of cellulose fibers that are suspended in insulating oil in transformers as samples that could be useful for assessing the aging degradation of insulating paper in transformers.**

We would like to note that the thermal degradation of insulating paper accompanies the crystallization of cellulose fibers.

In this paper, we used the dispersion staining method to investigate the relationship between degradation and crystallization of cellulose fiber.

***Index Terms*—Diagnosis, Power Transformers, degradation, Aging, Insulating Paper, Cellulose, Refractive Index**

I. Introduction

According to the present diagnosis method for aging degradation of oil-immersed transformers, the degree of polymerization (DP) of insulating paper is assessed by measuring the amount of decomposition products from the insulating paper (CO_2, CO, Furfural) that dissolve in insulating oil [1] [2]. However, it has been found that the accuracy of this diagnosis method depends on the design of the equipment.

We took special note of cellulose fibers that are suspended in the insulating oil in transformers. We considered these fibers to be useful samples for assessing the DP, and studied a new diagnosis method for aging degradation of oil-immersed transformers by using those cellulose fibers. We measured the refractive indices of the cellulose fibers using a phase contrast dispersion microscope (PCDM), because aging degradation accompanies an increase in the refractive indices of the cellulose fibers. In this paper, the relationship between DP and refractive indices is described, and refractive indices of cellulose fibers suspended in insulating oil were measured.

II. The Relationship Between Aging Degradation Of Cellulose Fibers and Refractive Indices

The cellulose fibers that compose insulating paper are made up of conifers-cells. There is a crystalline region and amorphous region in cellulose fibers. Degraded (decomposed) cellulose molecules are released from their covalent bond restriction and engage in hydrogen bonding with other cellulose molecules (this is called re-crystallization). Degraded cellulose fibers thereby become high crystalline. Fig. 1 shows an illustration of cellulose fiber's degradation and its crystalline.

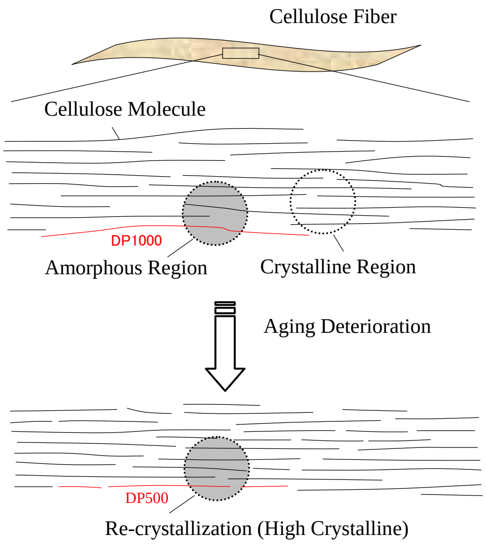

Fig. 1 Degradation of cellulose fiber and its crystalline.

It was assumed that the re-crystallization effect accompanied an increase of the Refractive Index (RI). Therefore, we expected that the RI would be an appropriate characteristic with which to estimate the degree of aging degradation of cellulose fibers.

III. Refractive Index Of Cellulose Fiber

To measure the RI of minute solids, one common method is a comparison of the difference of RI between minute solid and given-RI liquid.

It has been found that the RI of substances changes with the wavelength of light.

When cellulose fibers are immersed in liquid, the RI of these substances will correspond to a particular wavelength (see Fig. 2).

Fig. 3 shows oil-immersed cellulose fibers as seen through an optical microscope: (a) When the RI of oil is not in agreement with RI of cellulose fiber at an arbitrary wavelength, the outline

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M.Yoshida is with the Chubu Electric Power Co., 20-1, Kitasekiyama, Ohdaka- cho, Midori-ku, Nagoya, Japan (e-mail: Yoshida.Masanobu@chuden.co.jp)

Y.Konishi is with Yuka Industries Co., 2-34-17 Chidori, Ohta-ku, Tokyo, Japan(e-mail: y.konishi@yuka.co.jp)

of cellulose fiber will appear clearly, because light refracts at the boundary of two substances.

On the other hand, (b) When the RI of oil equals the RI of cellulose fiber at an arbitrary wavelength, the outline of cellulose fiber will not be clear, because light passes straight at the boundary of the two substances.

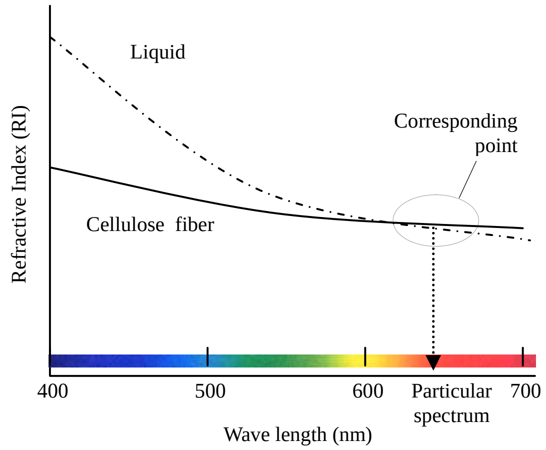
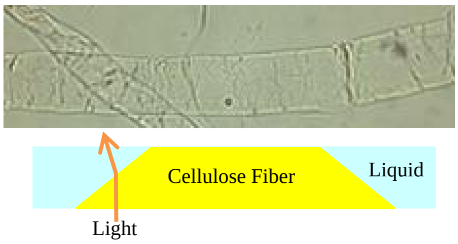
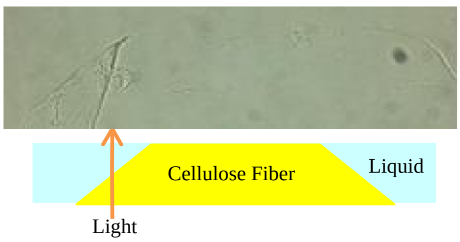


Fig. 2 Wavelength characteristics of substances' Refractive Indexes.



(a) RI of liquid does not equal RI of cellulose fiber.



(b) RI of liquid equals to RI of cellulose fiber.

Fig. 3: Refraction of light at a cellulose surface.

IV. Measurement of Refractive Index of Cellulose Fibers by Measuring the Dispersion Color

We measured the refractive indices of cellulose fibers using the Dispersion Staining Method (DSM).

DSM is a measuring method for the RI of solids. It is often used for qualitative analysis of asbestos.

The principle of DSM is as follows: When cellulose fibers are immersed in liquid, white light will be dispersed at the boundary of the two substances. At this point, there is a spectrum that does not refract (it passes straight through).

This particular spectrum has the condition: “RI of cellulose fiber = RI of immersion-liquid”.

When this particular spectrum is intercepted by an optical mask, and condenses the spectra that are not intercepted (See Fig. 4), the cellulose fiber appears to be colored.

This color is called "dispersion color".

The dispersion color is determined by the relationship of the RI between the cellulose fibers and immersion-liquid.

In other words, we can know the RI of cellulose fibers by observing the dispersion color, by using DSM.

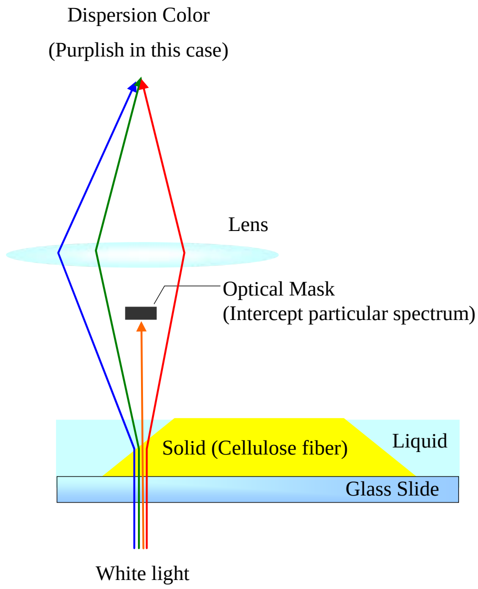


Fig. 4 The principle of DSM

V. Observation of Cellulose Fibers Using DSM

Figure 5 shows the procedure of observation for cellulose fibers using DSM.

Sample cellulose fibers were picked up from oil-removed insulating papers. These fibers were immersed with a given- RI liquid on the slide glass, and were observed using Phase Contrast Dispersion Microscope (PCDM).

We used an immersion-liquid prepared by Cargille laboratories. The RI of this immersion-liquid is 1.5900 at wavelength 589nm.

1. Remove insulating oil from insulating paper
2. Put the cellulose fibers on a slide
3. Drop some refractive index liquid
4. Observe dispersion color of the cellulose fibers using phase contrast dispersion microscope

Fig. 5 Flowchart

VI. Dispersion Color of Cellulose Fibers on New Insulating Paper

Fig. 6 shows the dispersion colors of new paper's cellulose fibers (DP of the paper is 1185).

Dispersion color appears at the edge of cellulose fiber, because light will disperse at the edge of the cellulose fiber.

Almost all of the cellulose fibers have a bluish dispersion color (see the left side of Fig. 6), while some cellulose fibers have a purplish dispersion (see right side).

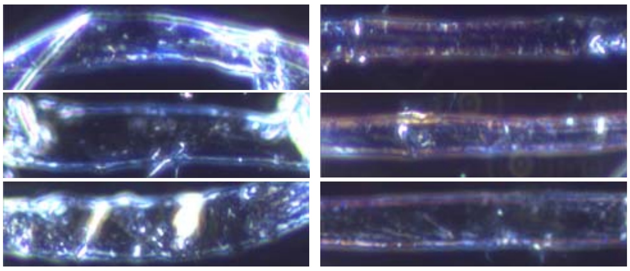


Fig.6 Observation of cellulose fibers using a phase contrast dispersion microscope (New insulating paper).

We observed the dispersion color of the cellulose fibers using a CCD camera.

We can use the CCD camera to convert the dispersion color into the intensity of three primary colors (red, green, blue) (See Fig. 7).

Fig. 8 shows the distribution of the dispersion color for 120 cellulose fibers on new insulating paper. The vertical axis and horizontal axis in Fig. 8 show the intesity rate of blue (b) and red (r) with the CCD camera, respectively (in this case r+g+b=1). We referred to this figure as "r-b characteristics".

In this figure, the dotted lines on r=1/3, b=1/3, g=1/3 are additional lines which enable to us see the distribution of the points easily.

Although we extracted the celullose fibers from an identical sheet of paper, the dispersion color of the fibers is not even.

We can know from this fact that crystallinity (degradation) of the individual cellulose fiber is not even.

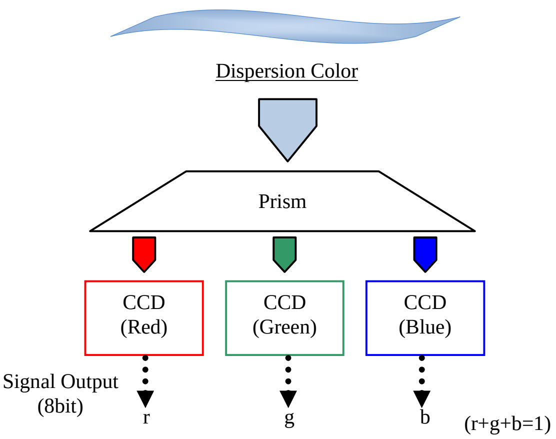


Fig. 7 Evaluation of dispersion color

Almost all celullose fibers are plotted within the b>0.33 area in Fig. 8. This result agrees with the fact that the dispersion colors of the fibers are bluish.

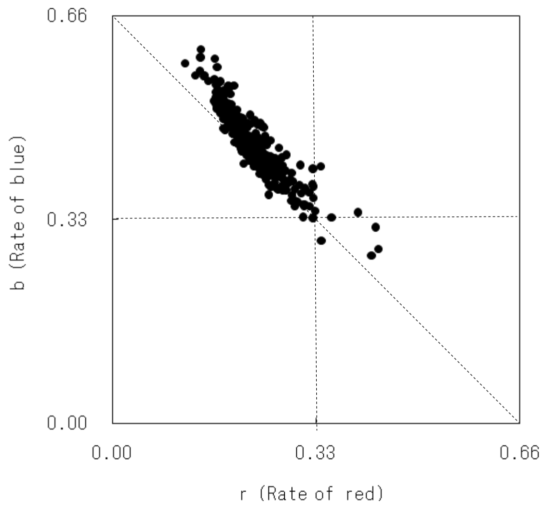


Fig.8 r-b characteristics of cellulose fibers (DP: 1185)

VII. Dispersion Color of Cellulose Fibers on Degraded Insulation Paper

Figs. 9 and 10 show the dispersion colors of cellulose fibers and the distribution of 150 cellulose fibers picked up from degraded insulating paper, respectively. (DP of the degraded paper is 170.)

In the case of degraded paper, many celullose fibers have a reddish dispersion color as shown in Fig. 9 (see right side) while some fibers have a bluish dispersion color (see left side).

In Fig. 10, the distribution area of the dispersion color is wider than that of new insulating paper (Fig. 8). The plotted area has a tendency to be shifted to the lower right. Consequently, there are many cellulose fibers in the r>0.33 (reddish) area.

The feature of dispersion color on degraded cellulose fiber is obviously different from that of the new paper.

These results show that it is possibile to assess the DP of insulating paper by measuring the dispersion colors of hundreds of cellulose fibers.

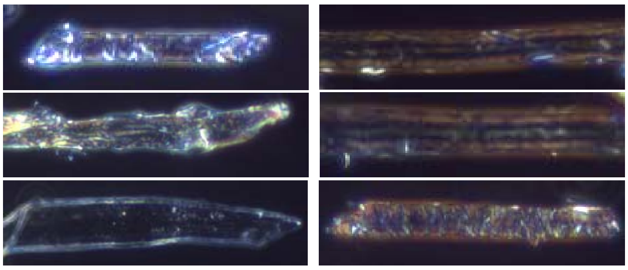


Fig. 9 Observation of cellulose fibers using a phase contrast dispersion microscope (Degraded insulating paper).

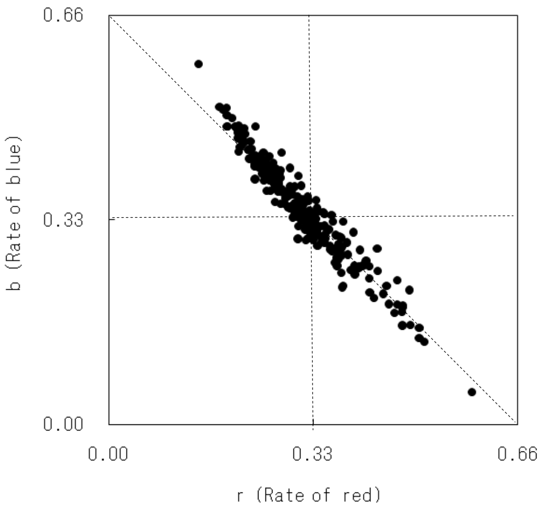


Fig.10 r-b characteristics of cellulose fibers (DP: 170)

VIII. Understanding of the Relationship Between Degradation of Insulating Paper and Dispersion Color of Cellulose Fibers

In this chapter, we showed that there is a tendency for degraded cellulose fiber to have a reddish dispersion color. Hereafter we will try to explain a theoretical understanding of this phenomenon.

Fig. 11 shows the relationship between RI characteristics of cellulose fiber and those of immersion liquid. When cellulose fiber is not degraded, the fiber has low RI; this is because it has an amorphous region to some degree (See Fig. 1). The immersion liquid's RI and cellulose fiber's RI would correspond at long wavelengths as per Fig. 11 (a). In such cases, the dispersion color would be bluish because long wavelength light would be intercepted from white light.

On the other hand, the degraded cellulose fiber has high RI because it has high crystalline. The immersion liquid's RI and cellulose fiber's RI would correspond at low wavelengths as per Fig. 11 (b). In such a scenario, the dispersion color would be reddish as short wavelength light would be intercepted from white light.

This explanation corresponds with experiment results, which are as follows:

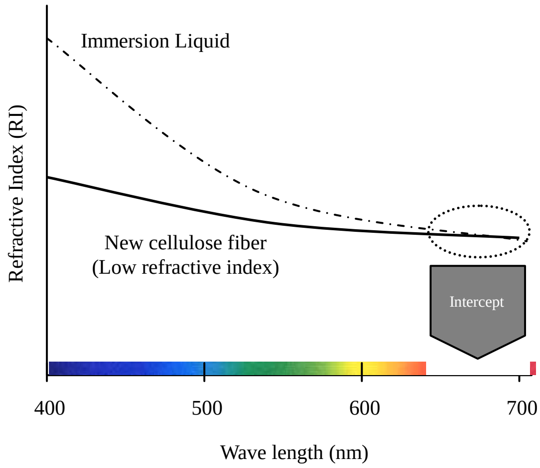
i) On the new paper, almost all of the plot in Fig. 8 is found in the b>0.33 area.

ii) On the degraded paper, there are many cellulose fibers in the r>0.33 area seen in Fig. 10.

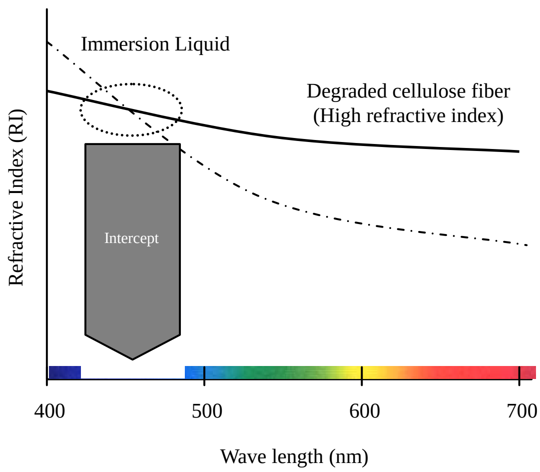
Fig. 12 shows the theoretical degradation orbit of dispersion color on r-b characteristics.

In this figure, we referred to the intersection of additional lines (r=1/3, b=1/3, g=1/3) as the "origin".

This origin corresponds to "white color". When the RI of cellulose fiber corresponds to that of immersion-liquid via invisible rays (IR or UV), the dispersion color would be the origin. This is because visible rays would not be intercepted by the optical mask.



(a) At the new cellulose fiber; The RI of immersion liquid's and cellulose fiber's correspond at long wavelength



(b) At the degraded cellulose fiber; The RI of immersion liquid's and cellulose fiber's correspond at short wavelength

Fig.11 Relation of refractive index characteristics between cellulose fiber and immersion liquid

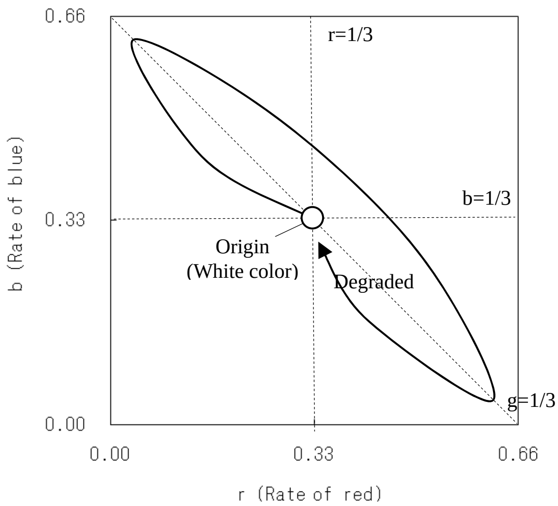


Fig. 12 Schematic figure of degraded orbit on r-b characteristics of dispersion color

In other words, when the RI of the cellulose fiber was extremely high (degraded) or extremely low (not degraded), it would be plotted to the origin.

The dispersion color is off the origin at the medium degradation (RI) condition of cellulose fiber. The point of dispersion color on r-b characteristics would follow the arrow of cellulose fiber's degradation.

IX. Dispersion Color of Cellulose Fibers Suspended in The Insulating Oil in Transformers

We took hundreds of cellulose fibers from insulating oil in transformers, and observed their dispersion colors. Fig. 13 shows the distribution of the dispersion color of cellulose fiber in a young transformer (3 years old) and in a middle-aged transformer (21 years old).

From this figure, almost all of the cellulose fibers in the young transformer were plotted within the b>0.33 area, which is similar to the new paper's distribution (see Fig. 8).

The load factor of this young transformer is low (about 40% average), the DP of its insulating paper could be assumed to around 1000.

On the other hand, cellulose fibers in the middle-aged transformer have lower blue rates than those found in the young transformer, and some fibers have reddish dispersion color (r>0.33).

We broke up this middle-aged transformer and identified the DP of its insulating paper as 610-700.

The distribution of r-b characteristics on these two transformers is clearly different.

This results show that it is possible to diagnose the aging degradation of oil-immersed transformers by using cellulose fibers that are suspended in the insulating oil in transformers.

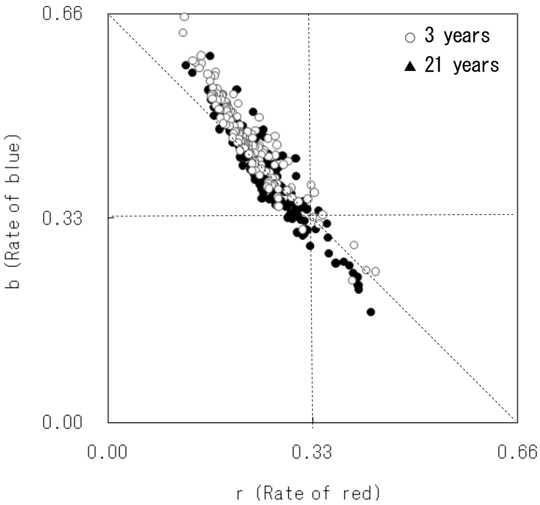


Fig.13 r-b characteristics of cellulose fibers in the insulating oil in transformer

X. Conclusion

We have shown that the aging degradation of cellulose fibers accompanies a change of the dispersion color.

These results show that we can assess the DP of insulating paper by measuring the dispersion colors of cellulose fibers.

In addition, we measured the dispersion color of cellulose fibers suspended in insulating oil in power transformers, and found that it presents the possibility of diagnosing the aging degradation of oil-immersed transformers.

References

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Masanobu Yoshida is a research engineer. He graduated from Nagoya University. He belongs to the electric power research & development center at Chubu Electric Power Co. He researches new diagnosis methods for power equipment in substations.

Yosinori Konishi , Ph.D. in Engineering, 2001, the University of Tokyo. He belongs to the development group at Yuka Industries Co. He researches the diagnosis of degradation in power transformers and the detection of disorders in oil immersed equipment.