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Modified Expression of Moisture Diffusion Factor for Non-Oil-Immersed Insulation Paper

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ABSTRACT Studying the moisture diffusion in non-oil-immersed insulation paper is helpful to optimize the drying process and improve the drying efficiency of oil-immersed equipment. Moisture diffusion factor (MDF) is the key parameter to describe the moisture diffusion in non-oil-immersed insulation paper. Thermal aging affects the moisture absorption capacity of insulation paper obviously, thus, this paper intends to modify the empirical expression of MDF by considering the effects of thermal aging. The transient moisture contents of non-oil-immersed insulation paper with different thicknesses were measured at 40 °C and 60 °C, respectively. Then, the experimental values of MDF were extracted, and the empirical expression of MDF was modified by considering the effects of thermal aging. Finally, the modified expression of MDF was verified. The following conclusion can be obtained: 1) the equilibrium time constant of non-oil-immersed insulation paper increases with thermal aging; 2) the moisture absorption rate of non-oil-immersed insulation paper decreases with thermal aging, and; 3) the modified expression of MDF is reasonable and effective.

INDEX TERMS Non-oil-immersed insulation paper, moisture diffusion factor (MDF), thermal aging, modified expression, equilibrium time constant.

I. INTRODUCTION

Insulation paper and insulation oil are the most important insulation materials used in oil-immersed transformers and oil-immersed bushings [1]–[3]. In oil-paper insulation system, it has been realized that insulation paper has stronger moisture absorption capacity than insulation oil [4]. For insulation paper, moisture is a harmful agent that catalyzes the thermal aging reactions and accelerates the aging process, which reduces the dielectric strength, decreases the partial-discharge inception voltage and increases the fault probability [5], [6]. What's worse is that during the thermal aging of insulation paper, the breakage of its cellulose chains produces more moisture, thus a self-supplied cycle can be generated for moisture in insulation paper. Additionally, for field equipment, moisture intrusion from environment is another major source. Therefore, controlling the moisture content in oil-immersed equipment is an important issue concerned by many scholars and engineers.

In the production process, new equipment must be dried before vacuum immersion with insulation oil [7], [8]. Taking the oil-immersed transformer as an example, the moisture content of dried insulation paper should be about 0.5%. Besides, according to IEEE Std. C57.91-2011, the operating oil-immersed transformer must be offline and returned to the factory for drying when its moisture content exceeds 4%. For oil-immersed equipment, there are several drying methods, such as hot air drying, hot oil spray, low frequency heating, and vacuum vapor phase drying [9]. Currently, hot air drying is the most widely used method in factory. Removal of insulation oil is the first step in the drying process, and then a hot, dry air flow is forced through the non-oil-immersed insulation paper. Thus, the moisture in solid insulation can be extracted by coming into contact with the hot, dry air flow. Afterwards, the humid air will be evacuated from the equipment and cooled to condense the extracted moisture. Finally, the air is heated to repeat the drying process again until the moisture content meets requirement. To improve the drying efficiency and optimize the drying process, many scholars have studied the moisture diffusion in non-oil-immersed insulation paper [10]–[12]. Fick's second diffusion law is the recognized model to study moisture diffusion in insulation paper, in which the moisture diffusion factor (MDF) is the key parameter [13], [14]. The reported measurement of MDF for

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insulation paper was conducted by Ast, and the permeation method was used in the measurement [15]. Afterwards, an empirical expression for MDF in insulation paper was proposed by Guidi and Fullerton [16], in which the variables are temperature and local moisture content. Based on the results reported by Guidi and Fullerton, Foss and Du conducted experiments to determine the parameter values of the empirical expression for different insulation materials [17]–[19]. Subsequently, Garcia optimized the expression of MDF by considering the effects of thickness [20]. Additionally, some scholars gave the experimental values of MDF for insulation paper in forms of curves and tables [21]. Currently, the empirical expression of MDF is recognized as:

$$D(c, T) = D_1 \cdot \exp(kc - \frac{D_2}{T}) \tag{1}$$

here D_1 and D_2 are constants when the sample has fixed thickness; k is constant and equals 0.43 for non-oil-immersed insulation paper [20]; and T is temperature, the unit of which is Kelvin.

The above studies provide the basis for analysis of drying process, and they are helpful to optimize the drying process. Recently, it has been realized that thermal aging affects the moisture absorption capacity of insulation paper obviously [22]–[24], i.e., the hydrophilicity of insulation paper is worse with aging. The effects of thermal aging on the moisture diffusion and the equilibrium moisture content of oil-immersed insulation paper have been reported in [5], [14], [23]. However, the characteristics of moisture diffusion in non-oil-immersed insulation paper are different from that of oil-immersed insulation paper [22]. Therefore, the effects and characteristics of thermal aging on the moisture diffusion in non-oil-immersed insulation paper should be further studied. In particular, the expression of MDF should be studied by considering the effects of thermal aging, which is helpful to optimize the drying process and improve the drying efficiency.

The paper intends to modify the empirical expression of MDF by considering the effects of thermal aging. In Sec. II, the transient moisture contents of non-oil-immersed insulation paper with different thicknesses were measured. The experimental results were given and analyzed in Sec. III. Then, in Sec. IV, the experimental values of MDF were extracted, and the empirical expression of MDF was modified by considering the effects of thermal aging. Finally, the modified MDF was verified in Sec. V.

II. EXPERIMENTS

Fig 1. shows the major steps in the designed experiment, which can be mainly divided into three parts: preparations of experimental materials, accelerated thermal aging, and measurements of transient moisture contents. For ensuring the repeatability of experiments and the validity of measurements, each sample was prepared in triplicate and each measurement was carried out twice. The objective of designed experiment is to obtain the transient moisture contents of non-oil-immersed insulation paper. Then, the effects of thermal aging on the moisture diffusion in non-oil-immersed insulation paper can be analyzed. Moreover, the transient moisture contents can be used to extract the MDF.

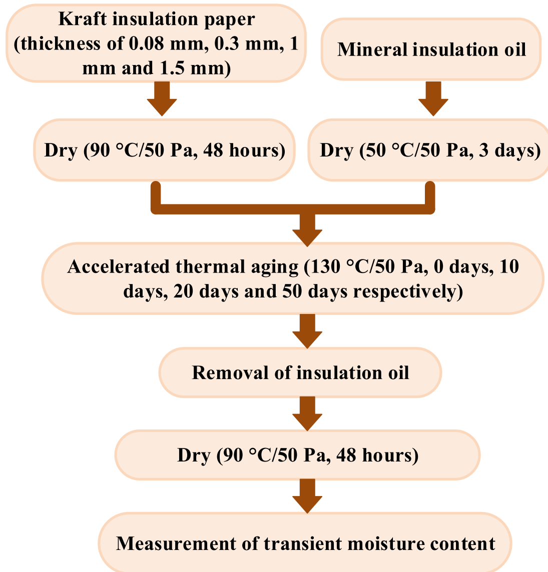

FIGURE 1. Flow chart of experiment.

A. PREPARATIONS OF EXPERIMENTAL MATERIALS

In the preparations of experimental materials, new Kraft insulation paper with different thicknesses (0.08 mm, 0.3 mm, 1 mm and 1.5 mm) and Karamay 25# naphthenic oil were employed, which are widely used in field oil-immersed equipment. The insulation paper with thicknesses of 0.08 mm, 0.3 mm and 1 mm were single-layer Kraft insulation paper, and the insulation paper with thickness of 1.5 mm was single-layer Kraft pressboard. First, the insulation paper with different thicknesses were cut into circular samples with diameter of 50 mm. Then, the insulation paper rounds without oil-immersion were placed in an oven and dried at 90°C/50 Pa for 48 hours. Subsequently, a part of dried paper rounds were used to conduct accelerated thermal aging directly, and the rest of dried samples were stored in a hermetically sealed bag to restrict the ingress of the oxidation agent and invasion of moisture. Finally, the insulation oil was dried at 50 °C/50 Pa for 3 day. The dried insulation oil was stored in a tank, and then the tank filled with dried oil was sealed by nitrogen.

According to IEC 60814, the moisture contents of dried insulation paper and insulation oil were measured by the Karl Fischer Coulometer C20 (Mettler Toledo Ltd.). The moisture content of dried insulation paper was 0.56%, and the moisture of dried insulation oil was 11 ppm.

B. ACCELERATED THERMAL AGING

The insulation paper rounds with the same thickness were immersed in a beaker filled with dried insulation oil. In our studies, a specific mass ratio of oil to paper (20:1) for each beaker was used. The beakers containing oil-paper insulation samples were placed in an oven for accelerated thermal aging at 130°C and 50 Pa. During the accelerated thermal aging experiment, the insulation paper rounds were sampled at 10th, 20th and 50th day respectively. For the sampled insulation paper rounds, oil-absorbing cotton was used to remove the absorbed insulation oil until the mass change tested by LE204E precision balance (Mettler Toledo Ltd.) was less than 0.5%. Afterwards, the insulation oil was removed again by using n-Heptane, and then the insulation paper rounds were stored in a hermetically sealed bag.

According to IEC standard, Degree of Polymerization (DP) is one of the indicators that reflects the thermal aging status of insulation paper [25]. Thus, the DPs of sampled specimens were measured using the Ubbelohde Viscometer based on IEC 60450.

C. MEASUREMENT OF TRANSIENT MOISTURE

Before conducting the measurement, the insulation paper rounds were dried at 90°C/50 pa for 48 h again to reduce the effect of initial moisture. The moisture content of dried insulation paper was 0.56%±0.03%. Then, the insulation paper rounds were placed in a testing box with constant temperature (40°C) and constant humidity (54% R.H.) to absorb moisture. The insulation paper rounds with thicknesses of 0.08 mm and 0.3 mm were sampled every 5 minutes, and the specimens with thicknesses of 1 mm and 1.5 mm were sampled every 30 minutes. The insulation paper rounds with the same thickness were totally sampled 10 times. Finally, the transient moisture contents were measured by using Karl Fischer Coulometer C20. Similarly, the same measurements for the transient moisture contents of insulation paper rounds were repeated at 60°C.

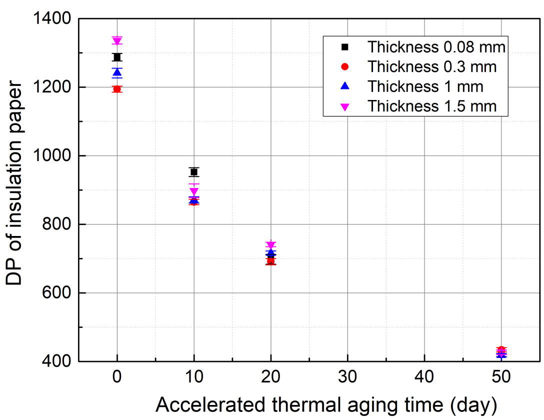

FIGURE 2. Measured DPs of the specimens.

III. EXPERIMENTAL RESULTS

A. ACCELERATED THERMAL AGING

Fig. 2 shows the measured DPs of the specimens after the accelerated thermal aging experiment. Out of Fig. 2, the changing tendency of DP is in consistent with the results reported in [26], [27]. Additionally, the lifespan of insulation paper can be estimated by the following empirical formula [26]:

$$L_{\text{act.\_life}} = L_{\text{acc.\_life}} \exp[-\alpha(T - T_0)] \tag{2}$$

here, $L_{\text{act.\_life}}$ and $L_{\text{acc.\_life}}$ are the lifespan under actual operating temperature and accelerated aging temperature respectively, T and T_0 are the actual operating temperature and accelerated aging temperature for insulation paper respectively, α is the thermal aging parameter of insulation paper which equals to 0.1155 [28]. Thus, on the basis of Eq. (2), the equivalent actual lifespan for the accelerated thermal aging experiment can be obtained as shown in Table 1.

TABLE 1. Results of accelerated thermal aging.

Aging time (days)	0	10	20	50
Equivalent aging time (under 80°C)	0 years	8.83 years	17.65 years	44 years

B. TRANSIENT MOISTURE CONTENTS

Fig. 3 shows the transient moisture contents of non-oil immersed insulation paper measured at 40 °C. Out Fig. 3, the moisture contents of specimens with thickness of 0.08 mm obtained equilibrium quickly. The specimens with thickness of 0.3 mm also obtained moisture equilibrium during the experiment. Conversely, the insulation paper rounds with thicknesses of 1 mm and 1.5 mm cannot obtain moisture equilibrium during the experiment. In terms of the effects of thermal aging, it can be seen that the equilibrium moisture content of specimens decreases with aging, which is in consistent with the results reported in [22]–[24]. Moreover, for the specimens with the same thickness sampled at the same time, the transient moisture content decreases with aging. It means that the moisture absorption rate of non-oil-immersed insulation paper decreases with thermal aging. Besides, the time needed to obtain moisture equilibrium (i.e., equilibrium time constant) increases with thermal aging. With respect to the thickness, it does not have effects on the equilibrium moisture content, however, the equilibrium time constant increases obviously with the increasing of thickness.

Fig. 4 shows the transient moisture contents measured at 60 °C. All of the specimens shown in Fig. 4 obtained moisture equilibrium during the experiment. The effects of thermal aging and thickness shown in Fig. 4 are in consistent with the phenomenon given in Fig. 3. Additionally, taking Fig.3 and Fig.4 into a comparison, both the equilibrium time constant and the equilibrium moisture content decrease with the increasing of experimental temperature. Compared with the effects of thermal aging on the moisture diffusion in oil-immersed insulation paper [14], [23], it can be found that the moisture absorption rate of oil-immersed insulation paper increases with aging, which is contrary to the phenomenon of non-oil-impregnated insulation paper. Therefore, the effects of thermal aging on the MDF of non-oil-immersed insulation paper is different from that of oil-immersed insulation paper.

IV. EXPRESSION MODIFICATION OF MDF BY CONSIDERING THERMAL AGING

A. MOISTURE DIFFUSION MODEL

Fick's second diffusion law is the recognized model to study moisture diffusion in insulation paper [13], [14]:

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left(D \cdot \frac{\partial c}{\partial x}\right) \tag{3}$$

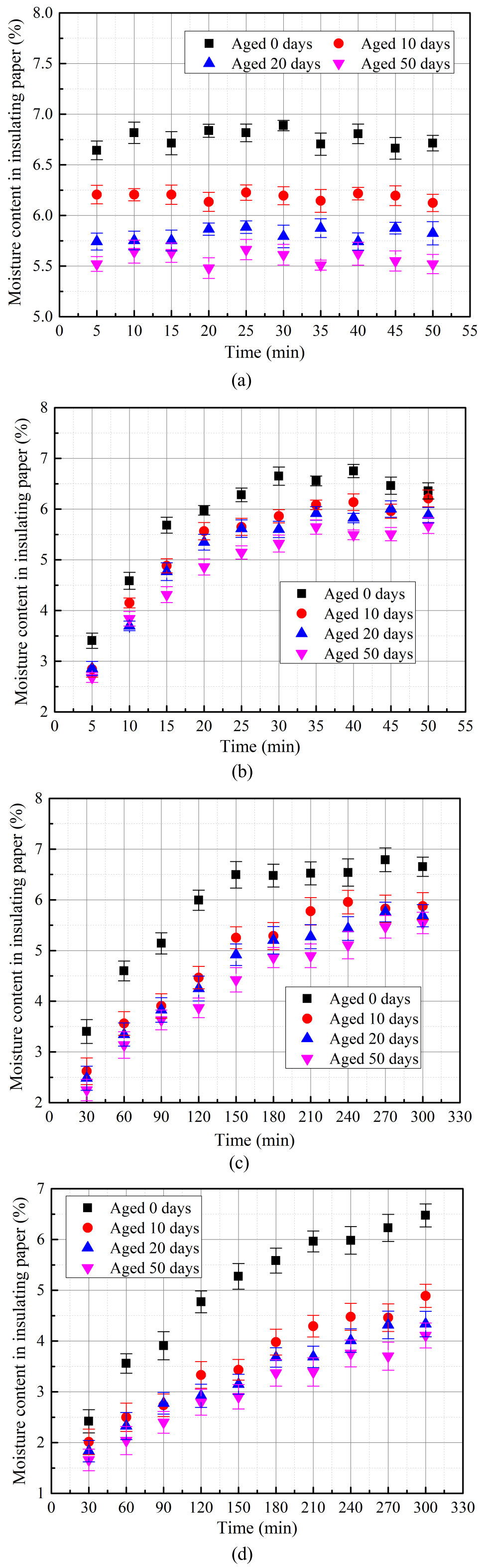

FIGURE 3. **Transient moisture contents at 40°C for insulation paper with different thickness: (a) 0.08 mm, (b) 0.3 mm, (c) 1 mm, and (d) 1.5 mm.**

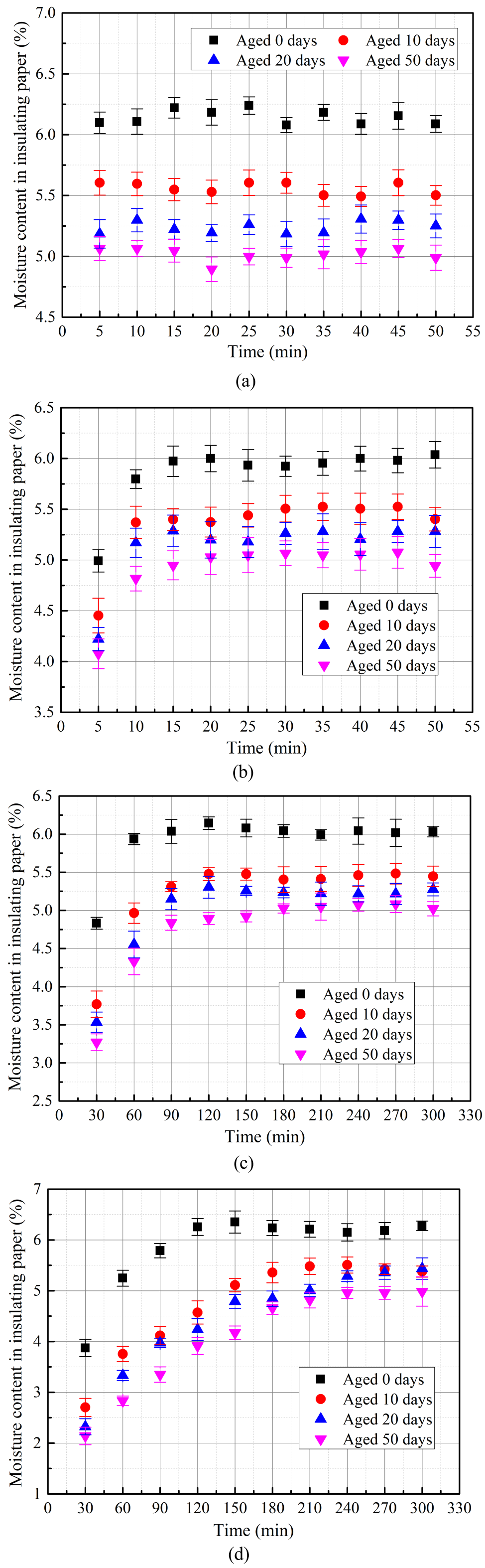

FIGURE 4. **Transient moisture contents at 60°C for insulation paper with different thickness: (a) 0.08 mm, (b) 0.3 mm, (c) 1 mm, and (d) 1.5 mm.**

here, c is the local moisture content; D is the moisture diffusion factor in the insulation paper, and its unit is m^2/s.

In this presented studies, on the basis of Eq. (3), the physical process of moisture diffusion in non-oil-immersed insulation paper was simulated by using COMSOL Multiphysics. The boundary conditions of established model were set as follows.

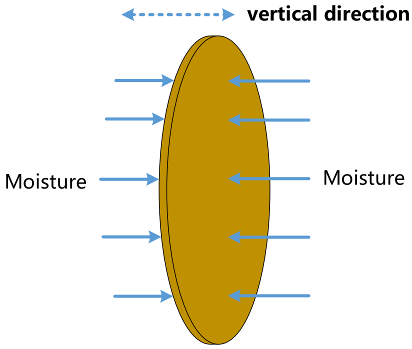

FIGURE 5. Moisture migration in the diffusion process.

1) Due to the areas of the upper and lower surfaces of the specimens are much larger than the side area, the moisture migration is mainly perpendicular to the upper and lower surfaces. Thus, as shown in Fig. 5, the moisture diffusion along vertical direction was only considered.
2) As shown in the experiment, before measuring the transient moisture content, the moisture content of dried insulation paper was 0.56%±0.03%. Thus, in the moisture diffusion model, the initial moisture content of insulation paper was set as 0.56%.
3) On the basis of finite element method, the moisture content of the surface of insulation paper in contact with air was the equilibrium moisture content, which can be expressed as [29]:

$$c_{boundary} = \frac{m \cdot a_w \cdot c_m \cdot N}{(1-m \cdot a_w) \cdot [1+m \cdot a_w \cdot (N-1)]} \cdot 100 \tag{4}$$

here, m is a parameter that takes into account the difference in the chemical potential between the multilayer and bulk water in material, which is equal to 0.716; a_{w} is the water activity which has the following relation with the relative humidity ($R.H.$): $R.H.=a_{\mathrm{w}} \cdot 100$; c_{m} is the monolayer moisture content; N is Guggenheim constant. The monolayer moisture content c_{m} has the following relation with DP [30]:

$$c_m = 0.0354 + 0.00306 \cdot \exp(DP/826.87) \tag{5}$$

The Guggenheim constant N has the following relation with temperature [30]:

$$N = 8.5 \cdot DP^{-0.0445} \cdot \exp[\frac{26587.77 - 5.315 \times DP}{R} \times (\frac{1}{T} - \frac{1}{T_{\mathrm{ref}}})] \tag{6}$$

here, R is the gas constant which is equal to 8.3144 J/(mol·K); T is the experimental temperature, and its unit is Kelvin; T_{ref} is the reference temperature which is equal to 323 K.

Additionally, the expression of MDF employed in the diffusion model is in consistent with Eq. (1).

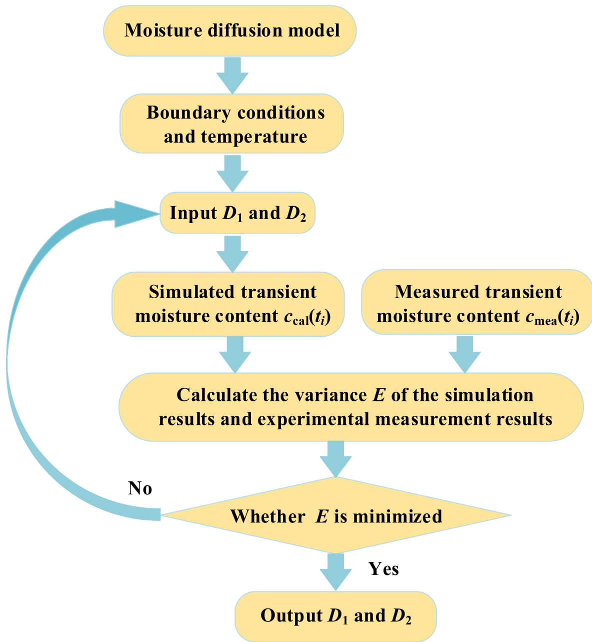

FIGURE 6. Extraction process of moisture diffusion factor.

B. EXTRACTIONS OF MDF BASED ON DIFFUSION MODEL

On the basis of reported studies in [20], Fig. 6 shows the extraction process of MDF based on diffusion model. In the fitting process, the optimal MDF of the specimens can be obtained by using the optimization objective factor E, which has the following expression:

$$E = \frac{1}{n}\sum_{i=1}^{n}[c_{\mathrm{mea}}(t_i) - c_{\mathrm{cal}}(t_i)]^2 \tag{7}$$

here $c_{\mathrm{mea}}(t_i)$ is the measured moisture content at time t_i; $c_{\mathrm{cal}}(t_i)$ is the calculated moisture content at time t_i. When the value of the established objective function is minimal, the value of MDF is the best.

TABLE 2. Fitting results of D_1 and D_2.

Thickness		Aging time (days)			
		0	10	20	50
0.08 mm	D_1	5.28e-3	4.61e-3	4.40e-3	4.29e-3
	D_2	6789.52	6730.16	6685.14	6636.06
0.3 mm	D_1	5.50e-3	4.79e-3	4.61e-3	4.45e-3
	D_2	6780.44	6728.81	6701.50	6661.16
1 mm	D_1	8.66e-3	6.20e-3	5.71e-3	5.09e-3
	D_2	6820.29	6771.26	6752.87	6712.18
1.5 mm	D_1	1.14e-2	7.12e-3	6.39e-3	5.53e-3
	D_2	6892.33	6837.40	6817.70	6778.32

Table 2 shows the fitted results of D_1 and D_2 for specimens with different thicknesses. Taking the results at 40 °C as an example, Fig. 7 shows the fitted curves for transient moisture content. Out of Fig. 7, the fitted curves are close to the tested

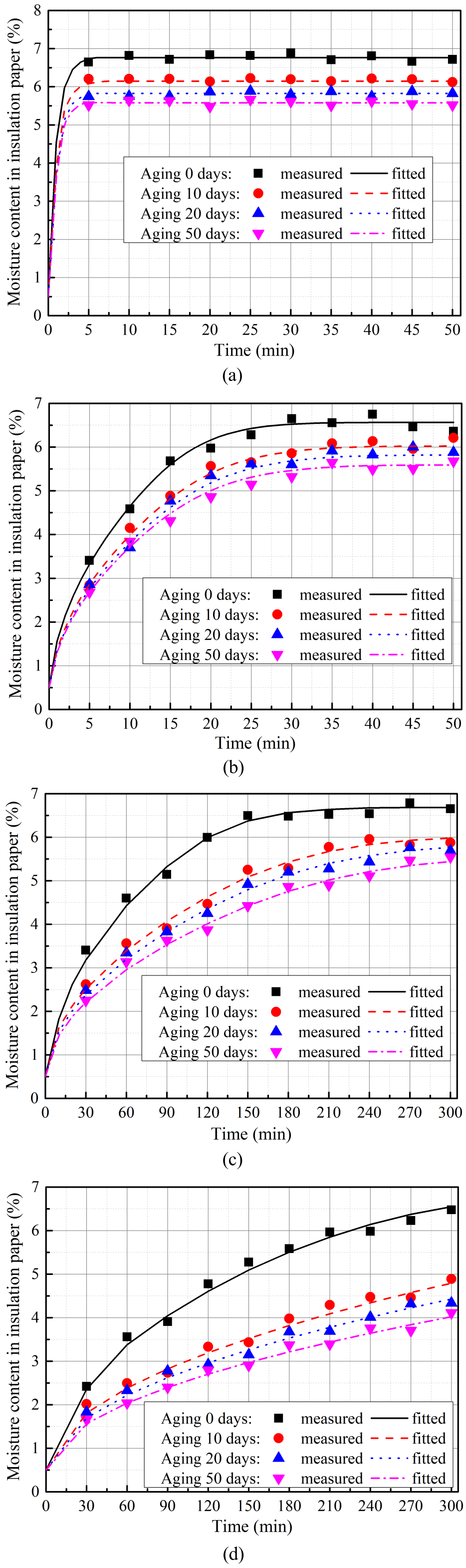

FIGURE 7. Fitted curves of transient moisture contents at 40°C for insulation paper with different thickness: (a) 0.08 mm, (b) 0.3 mm, (c) 1 mm, and (d) 1.5 mm.

results, and the relative errors between the fitted and the measured values are less than 5%. Thus, it can be concluded that the extracted D_1 and D_2 are acceptable and reasonable.

TABLE 3. Equilibrium time constant of moisture diffusion for different conditions.

Thickness	T	Equilibrium time constant (min)			
		0 days	10 days	20 days	50 days
0.08 mm	40 °C	4	4	5	5
	60 °C	2	2	2	2
0.3 mm	40 °C	41	41	43	45
	60 °C	13	15	15	16
1 mm	40 °C	240	380	410	450
	60 °C	80	135	145	150
1.5 mm	40 °C	750	840	960	1020
	60 °C	150	270	300	360

TABLE 4. Equilibrium moisture contents of non-oil-immersed insulation paper for different conditions.

Thickness	T	Equilibrium moisture content			
		0 days	10 days	20 days	50 days
0.08 mm	40 °C	6.76%	6.14%	5.82%	5.58%
	60 °C	6.16%	5.56%	5.24%	5.01%
0.3 mm	40 °C	6.57%	6.02%	5.82%	5.59%
	60 °C	5.97%	5.44%	5.23%	5.01%
1 mm	40 °C	6.66%	6.03%	5.84%	5.58%
	60 °C	6.07%	5.45%	5.26%	5%
1.5 mm	40 °C	6.88%	6.07%	5.87%	5.59%
	60 °C	6.28%	5.48%	5.29%	5%

Additionally, the equilibrium time constants and equilibrium moisture contents for different specimens can be obtained in the fitted results. Table 3 and Table 4 show the results respectively, and the changing tendencies given in Table 3 and Table 4 are in consistent with the analysis in Sec. III. Namely, the equilibrium time constant increases with thermal aging and thickness of insulation paper, however, it decreases with the increasing of temperature. Besides, the equilibrium moisture content decreases with aging, and it also decreases with the increasing of temperature.

C. MODIFICATION

As shown in Fig. 8, the values of D_1 and D_2 were plotted against DP respectively, moreover, the values of D_1 and D_2 were fitted. Out of Fig. 8, the values of D_1 have an exponential relation with DP, and the values of D_2 have a linear relationship with DP. The relations can be expressed as:

$$D_1 = a_1 \exp(DP/a_2) + a_3 \tag{8}$$

$$D_2 = b_1 DP + b_2 \tag{9}$$

here, a_1, a_2, a_3, b_1, b_2 are parameters related to the thickness, and they are constants when the thickness is fixed.

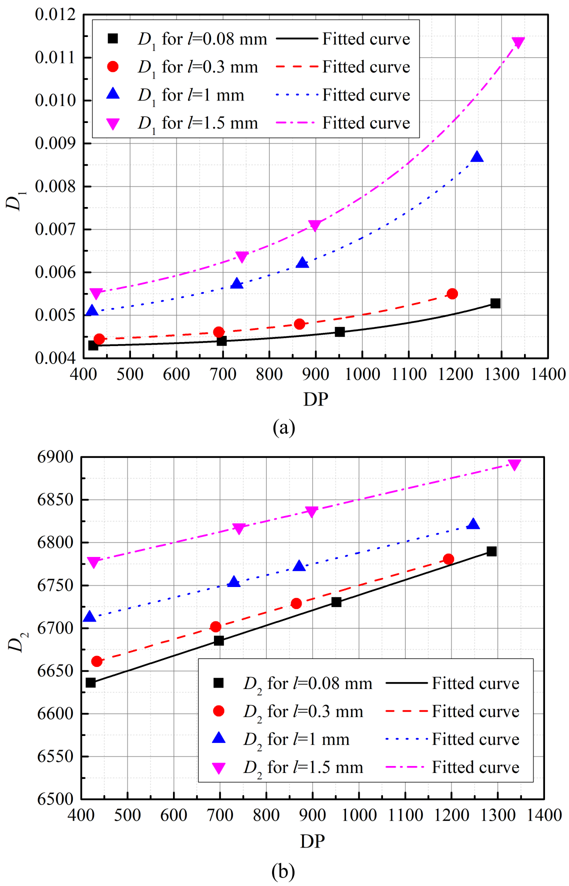

FIGURE 8. Effects of aging on D1 and D2. (a) Effects of thermal aging on D_1. (b) Effects of aging on D_2.

TABLE 5. Values of parameters in equations (8) and (9).

Thickness	Parameter				
	a_1	a_2	a_3	b_1	b_2
0.08 mm	2.43e-5	340.27	4.21e-3	0.177	6561.45
0.3 mm	5.32e-5	381.40	4.28e-3	0.157	6593.05
1 mm	2.03e-4	413.83	4.53e-3	0.131	6657.66
1.5 mm	2.87e-4	425.64	4.75e-3	0.125	6724.77

Table 5 shows the specific values of parameters in Eqs. (8) and (9) for the specimens with different thicknesses.

Out of Table 5, all of the parameters have relations with the thickness of specimens, thus the relations can be obtained by fitting the data in Table 5.

$$\begin{cases} a_1 = 1.97 \cdot 10^{-4} \cdot l^{0.96} \\ a_2 = -104.38 \cdot \exp(-2.86l) + 423.95 \\ a_3 = 3.78 \cdot 10^{-4} \cdot l + 4.17 \cdot 10^{-3} \end{cases} \quad (10)$$

$$\begin{cases} b_1 = 0.065 \cdot \exp(-2.12l) + 0.1227 \\ b_2 = 110.82 \cdot l + 6554.44 \end{cases} \quad (11)$$

here l is the thickness of insulation paper, and its unit is millimeter.

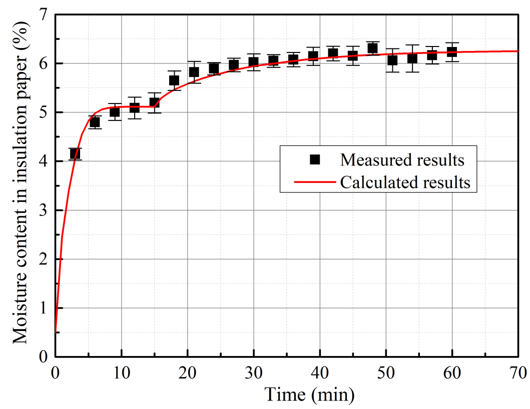

FIGURE 9. Measured and calculated results of the verification experiment.

Substituting Eq. (10) into Eq. (8), and Eq. (10) into Eq. (9), the following can be obtained:

$$D_1 = 1.97 \cdot 10^{-4} \cdot l^{0.96} \cdot \exp[\frac{DP}{423.95 - 104.38 \cdot \exp(-2.86l)}] + 3.78 \cdot 10^{-4} \cdot l + 4.17 \cdot 10^{-3} \quad (12)$$

$$D_2 = [0.065 \cdot \exp(-2.12l) + 0.1227] \cdot DP + 110.82 \cdot l + 6554.44 \quad (13)$$

Therefore, considering the effects of thermal aging, a general expression of MDF can be obtained as:

$$D(c, T, l, DP) = D_1(l, DP) \cdot \exp[0.43 \cdot c - \frac{D_2(l, DP)}{T}] \quad (14)$$

V. VERIFICATION

To testify the modified expression of MDF, an experiment under variable temperature condition was conducted. The specimens in the experiment were the insulation paper rounds with thickness of 0.3 mm and DP of 865. The initial moisture content was 0.58%. First, the specimens were placed in the testing box with initial temperature of 70 °C and relative humidity of 54%. Then, the temperature was changed to 30 °C 15 mins later. The insulation paper rounds were sampled to test moisture content for every 3 minutes, and there were totally 20 sampling times during the experiment. Thus, the transient moisture contents in this experiment can be obtained. Afterwards, the experimental conditions were inputted the moisture diffusion model, and the expression of MDF used Eq. (14). Finally, the calculated transient moisture contents can be obtained. Fig. 9 shows the measured and calculated results. Out of Fig. 9, the calculated results are close to the measured results. Moreover, the average relative error between measured and calculated results is less than 5%. Therefore, it can be concluded that the modified expression of MDF is reasonable and effective.

VI. CONCLUSION

The paper intends to modify the empirical expression of MDF by considering the effects of thermal aging.

By designing experiments, the transient moisture contents of non-oil-immersed insulation paper were measured and analyzed. Then, the experimental values of MDF were extracted, and the empirical expression of MDF was modified and verified. The following conclusion can be obtained: 1) the equilibrium time constant of non-oil-immersed insulation paper increases with thermal aging; 2) the moisture absorption rate of non-oil-immersed insulation paper decreases with thermal aging; 3) the modified expression of MDF is reasonable and effective.

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