APPLYING TIME-TEMPERATURE-MOISTURE SUPERPOSITION (TTMSP) METHOD TO IMPROVE THE LIFETIME MODEL ON THERMAL AGING OF OIL-PAPER

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Abstract: In order to improve the lifetime time model of oil-paper to obtain the more accurate prediction results, the influence of initial moisture contents and temperatures on aging properties of oil-paper was investigated. Firstly, oil-paper samples with four different moisture contents were aged at three temperatures. Degree of Polymerization (DP) of paper was measured as indicator of aging degree. The variation of DP with aging time was studied by introduction of kinetic equation of cellulose degradation accumulation. Secondly, based on the time-temperature superposition (TTSP) method, a time-temperature-moisture superposition (TTSMP) method was proposed to improve the lifetime model. It is indicated that by comparing with previous lifetime model, the merit of the improved one is that not only temperature but also initial moisture content in paper is considered, which is helpful for making more rational estimation of insulation lifetime during long time aging.

1. INTRODUCTION

Cellulose-based paper is widely used as electrical insulation in large electrical power transformers and cables. Thermal aging will directly cause the irreversible decrease of mechanical properties, while the breakdown strength does not change so much[1, 2]. Therefore, it is significant to investigate the thermal aging performance of oil paper insulation and its lifetime prediction methods at different operating condition [3-7]. To predict the insulation life, accelerate thermal aging test is often adopted. The variations of DP data at higher temperatures are used to get lifetime models, and these models are further applied to extrapolate the insulation life to a general operating temperature. However, these equations consider only the influence of temperature on the rate of cellulose degradation. The effects of moisture in cellulose are neglected, which will lead to a huge error of prediction.

In this study, a series of ageing experiments were performed on Kraft paper with different initial moisture contents in transformer oil over the temperature from 90 ℃ to 130 ℃. The degree of polymerization of the degraded cellulose was measured and these values were used to establish the corresponding kinetic model. The aim of this study is to improve the existing lifetime model and the corresponding data extrapolating method. By this improved method, the experimental data from accelerated tests can be extrapolated not only form higher temperatures to operating temperatures, but also from higher humidity level to lower one.

2. EXPERIMENTS

2.1 Materials and pre-processing

The insulation paper and oil used in this aging test are Kraft pulp paper, DLZ-U, by Yaan insulating material plant, China, and Naphthenic base transformer oil, by Kunlun KI25X by Kunlun lubricant, China. The papers were cut to tapes with dimension of 95×8cm, placed in a sealed chamber with 50% humidity and 25 ℃ for one month. After that, every paper tape was scrolled on a copper rod. The copper rod was 3mm diameter and 8cm long.

In this study four moisture content (0.5%,1%,3% and 5%) were chosen to investigate the influence of initial moisture content on the degradation rate of insulation paper in thermal aging process. The initial moisture contents were controlled by vacuum drying method. The detailed processing conditions are list in table 1.

Table.1 Pre-conditional process of oil-paper samples with four different initial moisture content

Moisture content *M*(%)	Processing condition
0.5	90℃ / 50Pa / 40h
1.0	90℃ / 50Pa / 24h
3.0	30℃ / 50Pa / 30% humidity/ 16h
5.0	40℃/ 30% humidity/48h

The paper scrolls were then be taken from vacuum chamber, combined with transformer oil (1:20 by weight), and put in glass bottles with 70 mL volume. After being vacuums impregnated at 40℃/50Pa for 24 hours, the bottles were finally sealed by applying epoxy adhesive on the covers under nitrogen, removed from the box, put into the aging ovens, and heated to 90, 110, or 130 °C to carry out the accelerated aging tests. During the aging tests, three samples were taken from aging ovens at intervals to measure DP of transformer paper according to ASTM D 4243-99 [8], and the average DP value was used to indicate sample's aging degree.

2.2 Degradation evolution equation applied to aging data

A degradation evolution equation developed by Ding and Wang is introduced in this research to study the kinetic process of cellulose aging[9].

$$\omega_{DP} = 1 - \frac{DP}{DP_0} = \omega^*_{DP}(1 - e^{-k_{DP}t}) \qquad (1)$$

Where ω_{DP} is the accumulated DP loss of cellulose, parameter ω^*_{DP} is the capacity of the DP degradation reservoir, the value of which can be determined by introducing the constraint condition ω_{DP} (t = t_f) = 1, t_f is the time to failure, k_{DP} (1/days) represents the DP degradation reaction rate of insulation paper.

Figure 1 shows plots of the DP change of samples during accelerated ageing at three temperatures, together with the corresponding model predictions using equation(1). For brevity, only the graph of 3% moisture contents were taken as examples and shown in figure 1. The estimated values of the parameters for each curve fitting are given in Table 2, with the values of all the regression coefficients $R^2 \geq 0.92$

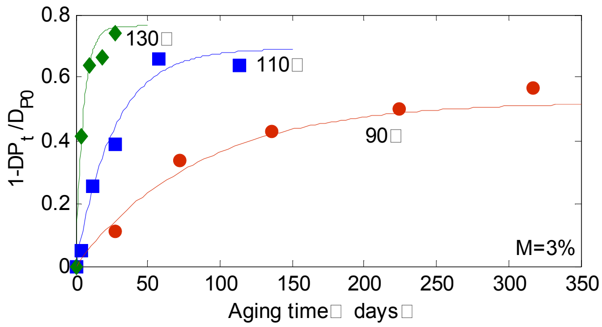

Figure 1. Fitting graph of experimental data according to equation(1)

Table.2 Fitting parameters of experimental data with equation (1)

M(%)	T(°C)	ω^*_{DP}	k_{DP}(1/day)	R^2
	90	0.3123	0.0101	0.98
0.5	110	0.6132	0.0210	0.99
	130	0.6908	0.0412	1.00
	90	0.4714	0.0107	0.97
1.0	110	0.6582	0.0247	0.99
	130	0.7316	0.0451	0.98
	90	0.5236	0.0118	0.95
3.0	110	0.6926	0.0375	0.97
	130	0.7643	0.1898	0.93
	90	0.6576	0.0132	0.92
5.0	110	0.7531	0.0452	0.99
	130	0.8229	0.2080	0.99

3. DATA EXTRAPOLATION BY TTMSP

The essential idea of accelerated aging tests is the assumption that the higher ageing temperature accelerates the changes in certain parameter of material microstructure in a uniform way. The ultimate goal is to predict parameter/property values at long times and low temperatures by extrapolating the parameter/property values obtained at short times and high temperatures. TTSP is one of the commonly used extrapolation method[10-12], the principle of which is mainly based on the Arrhenius equation:

$$k = A\exp(-\frac{E_a}{RT}) \qquad (2)$$

Where k is the reaction rate of the chemical degradation process under investigation, Ea the Arrhenius activation energy (J/mol) which represent the effective activation energy for the overall chemical kinetic expression governing the degradation, R the gas constant (8.314J/mol/K), T the absolute temperature and A the pre-exponential factor.

Combining the basic procedure of TTSP [13] and the degradation evolution equation by Ding and Wang, choosing 90°C as the reference temperature T_{ref}, the four TTSP mater curves of experimental data corresponding to four initial moisture contents are constructed. The parameters are listed in table 3. For brevity, only the master curve corresponding to 3% moisture contents is shown in figure 2.

Table.3 Fitting parameters of TTSP master curve with equation (1)

M (%)	T (°C)	α_T	ω^*_{DP}	$k_{DP}(\times10^{-3})$ (1/day)	Ea (kJ/mol)	R^2
	90	1				
0.5	110	5	0.6441	2.24	91.50	0.96
	130	20				
	90	1				
1.0	110	5	0.6800	4.28	86.31	0.95
	130	15				
	90	1				
3.0	110	4.8	0.7168	6.92	96.31	0.91
	130	25				
	90	1				
5.0	110	5	0.7691	9.51	91.51	0.97
	130	20				

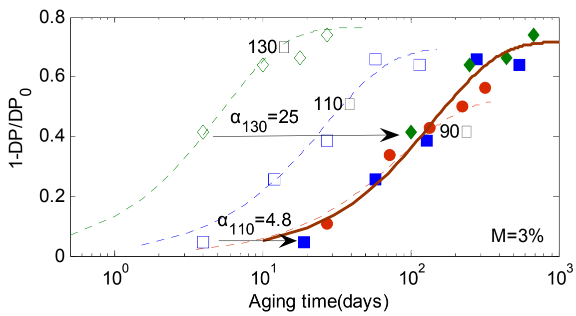

Figure 2. TTSP master curve of the experimental data from figure 1 using shift factors α_T

To take the influence of moisture into consideration, the four TTSP master curves are further shifted to the lowest moisture content, i.e. the reference moisture content M_{ref}=0.5%. This is accomplished by multiplying the degradation times of TTSP master curve by a moisture shift factor (α_M), which equals to shift the raw experimental data by multiplying the aging time with $\alpha_M \times \alpha_T$ to yield an approximately smooth TTMSP master curve. Figure 3 shows the TTMSP master curve and corresponding shifting factors, as well as the fitting parameters by equation(1). By plotting α_M vs M/M_{ref} , a power function $\alpha_M=(M/M_{ref})^b$ can be observed, shown in figure 4.

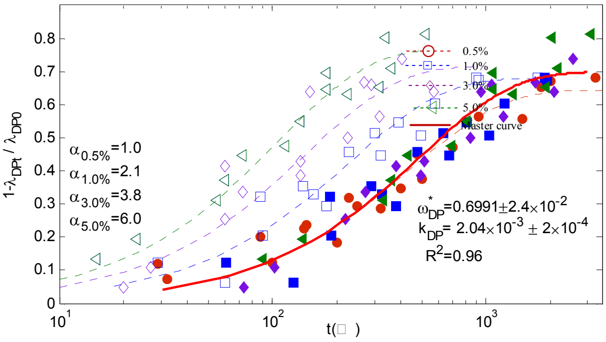

Figure.3 TTMSP master curve of data from Figure 2 using shift factors α_M

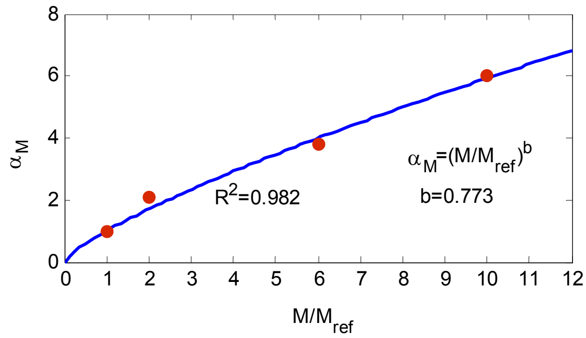

Figure 4. Variation of α_M with M/M_{ref}

According to TTMSP, an improved lifetime model of insulation paper can be obtained as shown in equation (3)

$$\begin{cases} \alpha_T = \exp(\dfrac{\bar{E}_a}{R}(\dfrac{1}{T_{ref}} - \dfrac{1}{T})) \\ \alpha_M = (\dfrac{M}{M_{ref}})^b \\ \alpha_{T,M} = \alpha_T \times \alpha_M \\ \omega_{DP_{end}} = 1 - \dfrac{DP_{end}}{DP_0} \\ t_{T_{ref},M_{ref}} = -\ln(1 - \dfrac{\omega_{DP_{end}}}{\omega^*_{DP}}) / \bar{k}_{DP} \\ lifetime = \dfrac{t_{T_{ref},M_{ref}}}{\alpha_{T,M}} \end{cases} \tag{3}$$

4. CONCLUSION

From the results obtained in the present study, the following conclusions are drawn:

(1) The cellulose degradation kinetic equation, combining with the TTSP method can be applied in the studies of oil-paper insulation ageing.

(2) A time-temperature-moisture superposition method (TTMSP) is present to extrapolate the accelerated data to normal operating condition. In this method, a time-moisture shift factor α_M is introduced and proved to have exponential relationship with initial moisture content in paper.

(3) Based on the TTMSP method, an improved lifetime model on thermal aging of oil-paper insulation is presented.

5. ACKNOWLEDGMENTS

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