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Accelerated Heating Paper Pressboard and Transformer Oil for Transformer Aging Assessment

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ABSTRACT

Paper pressboard is one of the main insulating elements that need to be investigated in order to identify the life span of high voltage transformer. In actual condition, the pressboard insulation is sealed in an enclosed metal container and immersed in transformer oil. Over the time, the pressboard insulation will degrade its performance and some part of pressboard polymeric compounds disbursed into its surrounding oil and some parts of oil compounds absorbed into the pressboard. This phenomenon can be analyzed and measured with its degree of polymerization (DP). Where DP is a measure of the chain length of the cellulose macromolecules, and is correlated to the mechanical strength of the paper and also can be correlated to transformer aging assessment. Based on reviews and reports, heat was believed to be the main cause of pressboard degradation in high voltage transformer. The correlation of heat and DP is difficult to obtain while a transformer is under commissioning, as this would need for the transformer to fully dismantle and extract the pressboard at the point of interest; as this is impossible at any circumstances, unless the transformer has undergone forensic investigation if total failure occurred. Therefore, this paper is presenting a technique under accelerated heating process in order to investigate the correlation of degraded paper pressboard and heated transformer oil under an influenced of controlled heat. A newly pressboard paper insulation was cut into pieces and undergone heating process immersed in transformer oil with predetermined heating hours. The pressboard and oil specimens were then put under difference tests, namely DP, furan compound, oil colour, neutralization value and water saturation. The results show good flag above the average until 288 hours heating process with reducing DP value. This give an indication that the heating element was certainly the main parameter of aging process based on the correlation of test parameter versus aging time.

Keywords: Accelerated aging process; pressboard insulation; high voltage transformer

INTRODUCTION

High voltage transformer is among the main apparatus in power generation and transmission, in bringing the electrical energy from source to load customers. It became the most important apparatus as it has very complicated structure and high cost of manufacturing process. The design of a single high voltage transformer may up between 20 to 30 years of life, however with proper maintenance it can be prolonged longer than that. The longer the life means it will degrade its performance and increases the risk of insulation failures. These insulation failures can be triggered by several causes, high voltage stress, heavy mechanical stress and prolong heat. These factors will eventually degrade the performance of winding insulations, reduce withstand capability and consequently reduce the lifespan of the transformer (Saha & Pukait 2017).

Thus insulation degradation becomes main concern and focus of investigations. Most standards for transformer are concentrated on condition assessment such as Degree of Polymerization (DP), Furan Analysis (FA) with high performance liquid chromatography, transformer oil colour and moisture content. It is however at some practical point of view, the assessment condition may still not be practical especially assessment during online measurement, in which continuous and long assessment may be needed in order to see and predict the trend of aging insulation. Long and real time assessment may require permanent type of instrument that can be installed permanently and controllable from a remote controlled desk. However such a system is still very limited and may not be possible for certain type of measurement and assessment technique which would require intrusive and shutdown of transformer; eg. FA and DP , that can only be done during total failure; which unlikely event allowed. (Kaliappan, G. & Rengaraj, M. 2021; Metwally, I. A. 2011; Joshi et al. 2012; Cheng et al. 2018; Liao et al. 2009; Ruijin et al. 2019; Wang et al. 2018; Christian, B. & Glaser, A. 2017; Mehta et al. 2016; Christian,B. & Glaser, A. 2017)

DEGREE OF POLYMERIZATION (DP)

Most paper insulation and pressboard insulation used are made from cellulose which is the most common natural polymer existed. Paper cellulose is polymer type made up of long chain molecules linked together of C-1 to C-4 bridges of oxygen. The repeating unit of the polymer chain linked together to form the cellulose polymer is referred to as the degree of polymerization. A cellulose based of new sample for paper pressboard insulation is thick and strong, with smooth surface without wrinkles. Under aging condition cellulose paper based will begin to show uneven thickness and has disorder characteristics and surface morphology began to appear rough (Wei et al. 2021).

DP is a characteristic measure of the cellulose chain that existed in paper type and pressboards used as insulation in oil-filled transformers. DP is a measure of the chain length of the cellulose macromolecules, and is correlated to the strength in mechanical of the paper. As cellulose insulation ages, the DP value gradually decreases, as does its mechanical strength. DP estimates, as measured by the simple laboratory testing method known as viscometry, can be used to gain insight into the state of decomposition of the cellulose and its remaining life (Wei et al. 2021; Ghoenim, S.S.M. 2021).

FURAN COMPOUND ANALYSIS (FA)

In the case of paper insulations undergone aging process, furan compound is part of substance partially dissolved in transformer oil. This process breaks the cellulose chain and shortening their length which consequently weakening the mechanical strength of paper insulations or pressboard paper. These compound indices are closely related to DP measurement at the same time. There are several furanic compounds that may associate to cellulose strength; however, the following TWO (2) furan compounds are mostly measured:

1. 2-furaldehyde (2FAL)
2. 5-hydroxymethyl-2-furaldehyde (5H2F)

The concentrations of these furanic compounds can be identified by using equipment known as liquid chromatography. This test is bounded with the standard such as ASTM D5837 and IEC 61198, in order to establish consistency of the results. Between the two compounds, 2FAL is always considered the main compound concentration of choice, since it is the most highly dissolved generation rate and its stability existed in transformer oil (Cheim et al. 2012; Abdul-Malek, Z. & Bashir, N. 2011).

TRANSFORMER OIL COLOUR

Colour of insulating oil indicates the deterioration level of insulation liquid transformer in used. This can be represented by a standard numerical value in comparison with standard colour series. In general, new oil under service is considered colourless, under aging condition the index colour is increasing which shows an indication of contamination or deterioration. In addition to colour standard, the transformer oil also may indicate other mixed substances like cloudiness or sediments. This give an indication of contamination exist during long aging process of transformer in operation. Figure 1 shows an example of transformer oil colour quality.

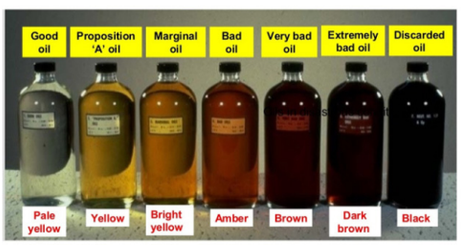

FIGURE 1. Transformer oil colour quality
Source: Mohd Aizam Talib (2022)

NEUTRALIZATION VALUE (ACIDITY TEST)

The neutralization value is based on acidity test of used transformer oil. It is a measure of contaminated free organic or inorganic acid present in the oil and expressed in terms of mgKOH/g of potassium hydroxide. High acid level means, the oil has been contaminated and oxidized with alien substances like paints, varnish or others, which may be due to corrosion of metal parts inside transformers. The used of acid test is for general guide to determine whether or not the oil should be replaced of reclaimed. It also gives an indication that the present of acid in transformer oil may accelerate the insulation degradation process for both transformer oil and paper insulation (Mohd Aizam Talib 2022).

MOISTURE CONTENT IN TRANSFORMER OIL

Water can exist in several different conditions within the transformer. This can be of many factors affecting the existence of water, the water soluble within paper insulation, improper treatment of water prior to commencement, high humidity or high temperature during transformer operation. There are known as three basics types of water content found in transformer oil:

1. Dissolved water due to hydrogen bonding to the hydrocarbon molecules.
2. Emulsified water saturation in oil solution, which not yet totally separated from the oil. It gives the oil to have a milky appearance.
3. Free water saturation in oil solution with high concentration to form water droplets separated from oil.

The detection of water in oil can be performed in laboratory scale with special equipment analytical technique called Karl Fischer titration and often performed by Moisture Meter from Metrohm based on method IEC60814 standard.

In relation to water content there is a term Relative Saturation (RS), which is a measure of water to the solubility level at certain temperature. It is expressed in percentage unit with respect to concentration of water that the oil can hold. The equation of RS in relation with actual water content is shown in Equation 1 as follows:

$$\%RS = 100 \times \frac{C_w}{C_{wsat\_T}} \quad (1)$$

Where C_w represents actual water content, and C_{wsat_T} represents concentration of water that the oil can hold at measurement temperature (Arsad et al. 2023; Du et al. 2001).

METHODOLOGY

SAMPLE PREPARATION AND EXPERIMENT

High density pressboard cellulose based was chosen for test sample and experiment. It is to fulfill the requirements of IEC 60641-3-1 and has 2mm of thickness. Figure 2 shows the pressboard sample prior to sample preparation. The pressboard was then cut into pieces to have 5mm × 5mm dimension.

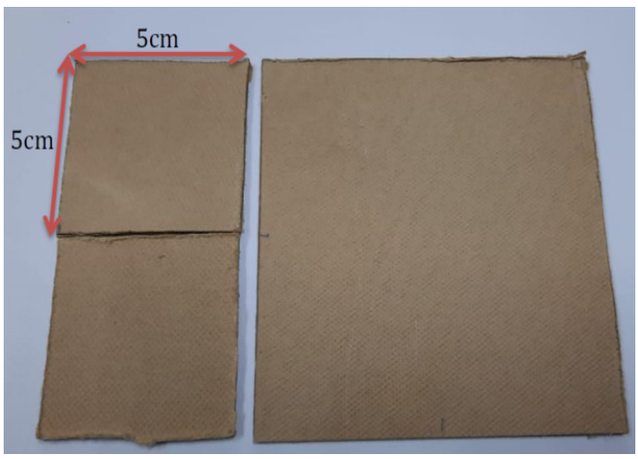

FIGURE 2. Pressboard sample

The pressboard pieces were prepared alongside with transformer mineral oil in a glass beaker of 500ml volume. The pressboard pieces were then immersed in new untreated mineral oil.

The oil is sealed with sticky aluminum foil and rest at room temperature for several minutes before aging heating process. The resting process is to clear for any bubble trapped within the beaker. Figure 3 shows the sealed mineral oil with immersed pressboard papers.

The sealed mineral oil and samples were placed in a hot oven as shown Figure 4. The aging temperature was set to 130^0C, and timing set to have a maximum of 288 hours. Table 1 shows the schedule samples taken out for every consecutive 48 hours, with all 6 samples.

FIGURE 3. Sealed untreated mineral oil with pressboard samples

FIGURE 4. Sealed untreated mineral oil and pressboard samples in hot oven

TABLE 1. Samples Preparation and Status

Samples	Hours	Date	Day	Status
All	0	12-Mar-21	Friday	IN
1	48	14-Mar-21	Sunday	OUT
2	96	16-Mar-21	Tuesday	OUT
3	144	18-Mar-21	Thursday	OUT
4	192	20-Mar-21	Saturday	OUT
5	240	22-Mar-21	Monday	OUT
6	288	24-Mar-21	Wednesday	OUT

RESULTS AND DISCUSSION

SAMPLE CHEMICAL TESTING

Each of the samples was sent for chemical testing. The followings were the suggested procedure chemical test for every sample undergone accelerated heating process:

1. Degree of Polymerization (DP)
2. Furan Compound Analysis (FA)
3. Transformer oil and pressboard colour comparision.
4. Neutralization Value (Acidity Test) and
5. Water Saturation level (Moisture Content)

Each of the test samples tabulated in Table 1 will carry out the suggested chemical test right after each sample taken out from the oven. The correlation analysis is carried out to see the effect of Thermal Aging Stress at different aging periods. The analysis is taken for untreated mineral oil exposed to high humidity at room temperature.

CORRELATION OF DEGREE OF POLYMERIZATION, DEGREE OF FURAN COMPOUND, UNDER AGING THERMAL PROCESS

The polymerization test was conducted for every aging time and tabulated in Table 2. Figure 5 shows the correlation analysis plot of DP against time aging factor. The results shows a decaying DP values over aging time which shows the bonding mechanical strength is weakening for longer aging period.

2-fufural (2FAL) analysis is tabulated in Table 3 and Figure 6 show the corresponding 2-FAL compound plot against aging time. 5-hydroxymethyl - 2-fufural (5H2F) analysis is tabulated in Table 4 and Figure 7 show the corresponding 5H2F compound plot against aging time. The total furan compound is tabulated in Table 5 and Figure 8 show the corresponding total compound plot against aging time. All of these results show the standard lab testing laboratory under said standard of ASTM D5837 and IEC 61198. These results give indications of furanic compound exist within transformer pressboard with higher concentration in transformer oil against aging time. Starting from Table 2 to Table 5, an additional parameter of cooling period has been added, it is to show how long the sample is at 'rest' before the actual test date.

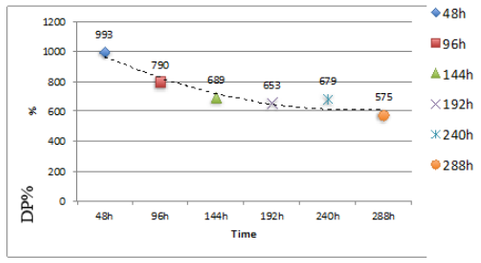

FIGURE 5. Degree of Polymerization against aging time

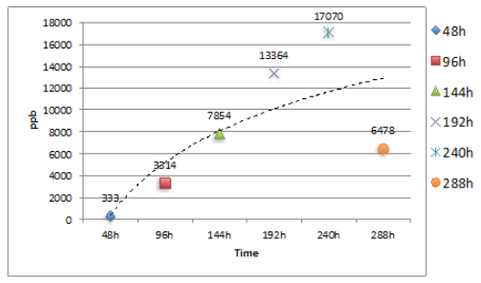

FIGURE 6. 2-fufural (2-FAL) against aging time

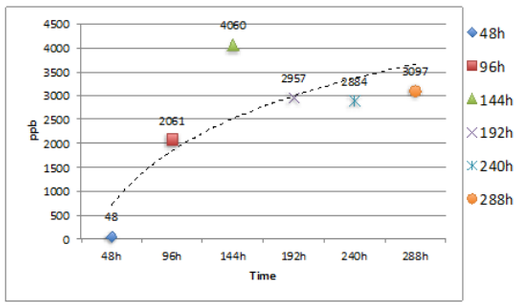

FIGURE 7. 5-hydroxymethyl-2-furfural (5H2F) against aging time

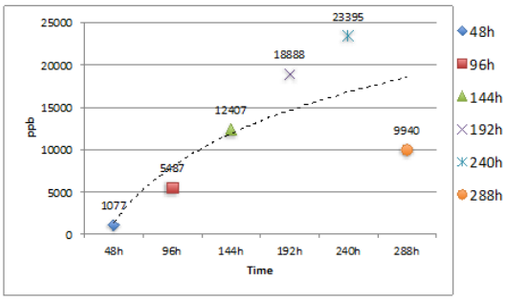

FIGURE 8: Total furan compound against aging time

TABLE 2. Degree of Polymerization

Time	Test	Result	Date In	Date Out	Test Date	Cooling Period
48h	%	993	12-Mar-21	14-Mar-21	26-Mar-21	288h
96h	%	790		16-Mar-21	26-Mar-21	240h
144h	%	689		18-Mar-21	26-Mar-21	192h
192h	%	653		20-Mar-21	26-Mar-21	144h
240h	%	679		22-Mar-21	26-Mar-21	96h
288h	%	575		24-Mar-21	30-Mar-21	144h

TABLE 3. Furan Compound; 2-fufural (2FAL)

Time	Test	Result	Date In	Date Out	Test Date	Cooling Period
48h	2-furfural (2FAL)	333	12-Mar-21	14-Mar-21	16-Mar-21	48h
96h		3314		16-Mar-21	17-Mar-21	24h
144h		7854		18-Mar-21	19-Mar-21	24h
192h		13364		20-Mar-21	23-Mar-21	72h
240h		17070		22-Mar-21	23-Mar-21	24h
288h		6478		24-Mar-21	25-Mar-21	24h

TABLE 4. Furan Compound; 5-hydroxymethyl-2-furfural (5H2F)

Time	Test	Result	Date In	Date Out	Test Date	Cooling Period
48h	5H2F	48	12-Mar-21	14-Mar-21	16-Mar-21	48h
96h		2061		16-Mar-21	17-Mar-21	24h
144h		4060		18-Mar-21	19-Mar-21	24h
192h		2957		20-Mar-21	23-Mar-21	72h
240h		2884		22-Mar-21	23-Mar-21	24h
288h		3097		24-Mar-21	25-Mar-21	24h

TABLE 5. Total Furan Compound

Time	Test	Result	Date In	Date Out	Test Date	Cooling Period
48h	Total of FURANs (ppb)	1077	12-Mar-21	14-Mar-21	16-Mar-21	48h
96h		5487		16-Mar-21	17-Mar-21	24h
144h		12407		18-Mar-21	19-Mar-21	24h
192h		18888		20-Mar-21	23-Mar-21	72h
240h		23395		22-Mar-21	23-Mar-21	24h
288h		9940		24-Mar-21	25-Mar-21	24h

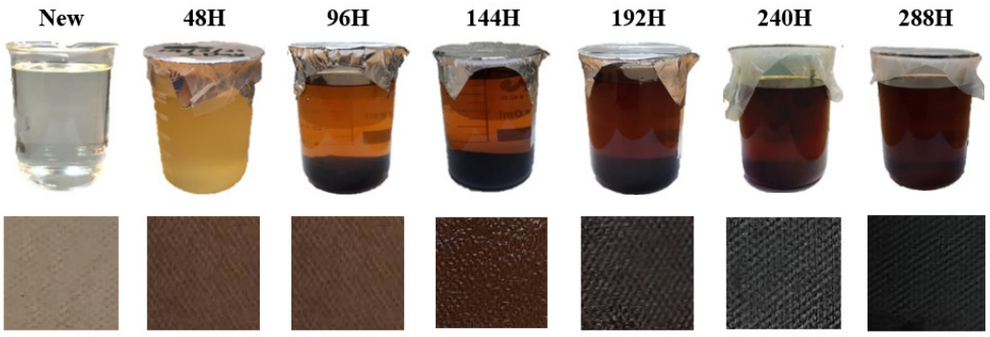

FIGURE 9. Oil Sample and Pressboard Sample Colour Test Results from 0H (New Oil) to 288H.

OIL SAMPLE AND PRESSBOARD SAMPLE COLOUR TEST RESULTS

Figure 9 shows the colour of oil sample and pressboard sample test results under different aging period. The comparison was made with new oil in order to see the transition of aging. The transition is in agreement with reference standard colour under aging effect as shown in Figure 1.

CORRELATION OF NEUTRALIZATION VALUE (ACIDITY TEST) UNDER AGING THERMAL PROCESS AND DEGREE OF POLYMERIZATION

The neutralization value (NV) also known as acidity test, is a measure of acid compound concentration in transformer oil. Table 6 tabulates the correlation between neutralization value with the aging thermal period. The correlation plot of both parameters is shown in Figure 10 which gives an indication of transformer oil becoming more acidic over a period under thermal stress.

The DP is the closed parameter that represents the aged parameter of cellulose based insulation in power transformer. Hence the study of correlation between the NV and the DP is to see the effect of oil aged effect to the cellulose compound component in pressboard paper. Figure 12 shows the relationship of the NV test to the degree of polymerization in cellulose pressboard paper. The relationship is based on the data tabulated in Table 2 and Table 6.

MOISTURE CONTENT UNDER AGING THERMAL PROCESS AND DEGREE OF POLYMERIZATION

Meanwhile, moisture content is a measure of water concentration in oil. This will indicate that the water content could be originally generated either from the initial condition itself or the cellulose based material immersed in it. Table 7 tabulates the correlation between moisture with the aging thermal period. The correlation plot of both parameters is shown in Figure 11. Meanwhile Figure 13 shows the percentage of relative saturation. Where relative saturation can be defined as the ratio of actual water content to the maximum oil can hold at that temperature. The water concentration result was based on Equation 1. The correlation of percentage of water saturation versus degree of polymerization is shown in Figure 13. The correlation data for %RS and DP were extracted from Table 2 and Table 7 respectively.

TABLE 6. Neutralization Value

Time	Test	Result	Flag	Ref (Max)	Date In	Date Out	Test Date	Cooling Period
48h	Neutralization Value (NV), mgKOH/g	0.034	Normal	0.3 mgKOH/g (Max)	12-Mar-21	14-Mar-21	16-Mar-21	48h
96h		0.0474	Normal			16-Mar-21	17-Mar-21	24h
144h		0.0557	Normal			18-Mar-21	19-Mar-21	24h
192h		0.0666	Normal			20-Mar-21	23-Mar-21	72h
240h		0.0709	Normal			22-Mar-21	23-Mar-21	24h
288h		0.0747	Normal			24-Mar-21	25-Mar-21	24h

TABLE 7. Moisture Content and Relative Saturation based on Equation 1

Time	Test	Result	Flag	Ref (Max)	Date In	Date Out	Test Date	Cooling Period	*%RS*
48h	Moisture (H2O), ppm	97	High	25	12-Mar-21	14-Mar-21	16-Mar-21	48h	388
96h		77	High	25		16-Mar-21	17-Mar-21	24h	308
144h		75	High	25		18-Mar-21	19-Mar-21	24h	300
192h		40	High	25		20-Mar-21	23-Mar-21	72h	160
240h		41	High	25		22-Mar-21	23-Mar-21	24h	164
288h		45	High	25		24-Mar-21	25-Mar-21	24h	180

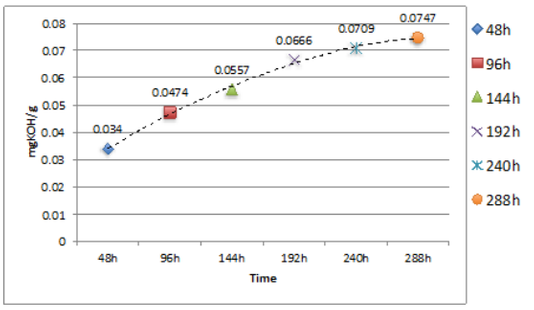

FIGURE 10. Neutralization value correlation with time under thermal stress

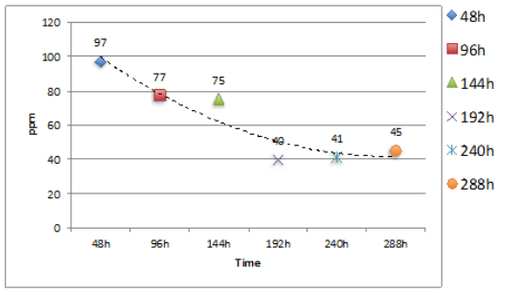

FIGURE 11. Moisture content correlation with time under thermal stress

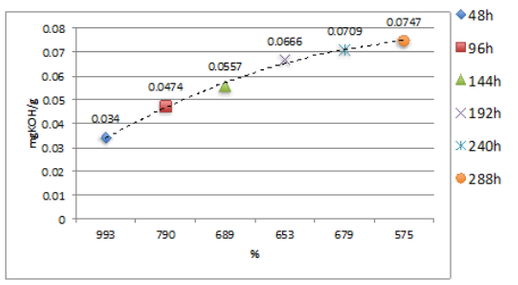

FIGURE 12. Neutralization Value vs Degree of Polymerization

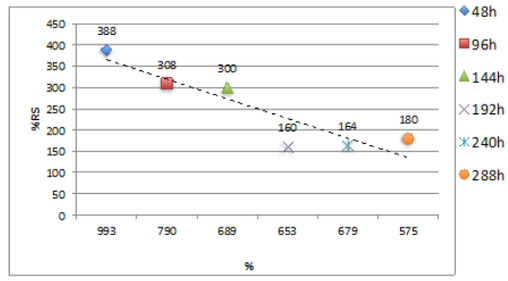

FIGURE 13. Percentage of water Saturation vs Degree of Polymerization

CONCLUSION

Cellulose aging assessment tests have been conducted with DP, furan analyses and aging colour. The DP was conducted with the aged paper degraded under thermal stress from 48h to 288h. The results show good flag above the average until 288h, with reducing DP versus accelerated aging time. On the contrary, under furan analyses the total furan compound showing incremental trend versus accelerated aging time. This shows higher concentration of furan compound existed in transformer oil against time. The furan measurements were actually conducted with the aging oil and the results are in agreement with the colour of the transformer oil, which becomes darker at difference accelerated aging time.

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DECLARATION OF COMPETING INTEREST

None.

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