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Thermal aging of solid insulation under dual temperature variation

Amit Kumar MEHTA*, **Ram Naresh SHARMA**, **Sushil CHAUHAN**
Department of Electrical Engineering, National Institute of Technology, Hamirpur, Himachal Pradesh, India

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Abstract: The power transformer is one of the most expensive pieces of equipment in a high-voltage AC power system. An adequate monitoring system for power transformers can help in reducing the failure rate and thereby enhance system reliability and economic efficiency. Long-term and accelerated aging is not possible in real transformers, so prorated models of real transformers are preferred. This paper presents a study aimed at the aging of different cellulose papers and pressboards impregnated with transformer oil subjected to accelerated thermal aging at an oil temperature of 120 °C and winding temperature of 150 °C for time intervals extending from 0 to 500 h. The study manifests a close relationship between the degree of polymerization and the tensile strength of paper and pressboard that could be used in predicting the condition of solid insulation at various elevated temperatures. The graphical representation of various solid insulation properties and their correlation analysis has also been carried out.

Key words: Power transformers, prorated models, thermal models, aging temperature, aging time, oil insulation, paper insulation, degree of polymerization, tensile strength

1. Introduction

The majority of power transformers in power systems are oil-filled and contain cellulose as an insulator. Transformer oil, besides cooling, also provides electrical insulation along with cellulose. Cellulose is an important and major constituent of paper and pressboard. As a transformer ages, it generates byproducts. These byproducts could affect transformer performance and increase the chance of failure. To protect transformers from sudden collapse, they are subjected to a large number of tests. To perform these tests, researchers have developed prorated models, prototype models, dual temperature aging model, ampoule models, and test cell models. Prorated models are built on long-term and short-term accelerated aging. The life of the transformer is actually the life of its internal insulation system. The most commonly used systems are liquid insulation (transformer oil) and solid insulation (kraft paper, pressboard, and wood, i.e. cellulose products). The insulation age of a transformer is exclusively decided by the life of cellulosic materials. The loading of a power transformer beyond the nameplate rating is commonly practiced by most utilities. The normal life expectancy loading can be performed until 120 °C. The planned loading is recommended without exceeding a maximum value of 130 °C. The long-time and short-time emergency loading is recommended without exceeding a maximum value of 140 °C and 180 °C, respectively. The maximum hot-spot temperature for bushing is 150 °C [1]. The flash point for mineral oil is also 150 °C. By considering all these overload capacities the highest winding temperature in this study is chosen as 150 °C.

*Correspondence: mehtaamit5@gmail.com

1.1. Proposed prorated test cell

Many researchers have developed different types of prototype test cells for estimating the age of the insulation system of a power transformer and they used ovens or hot plates to heat the samples. However, in the design of proposed test cell, care has been taken to replicate the conditions prevailing inside the actual transformer. The proposed test cell is designed to provide for separate aging of solid and liquid components. An electrical insulation system is subjected to test cycles at selected elevated temperatures. Each cycle comprises a specific time of exposure at the selected temperature and related diagnostic tests. The test cell usually consists of a current-carrying conductor, conductor insulation, insulation spacers/barriers, and liquid. The proposed cell is based on the standards IEC-62332 [2] and IEEE C57.100 [3], in which a current-carrying conductor is wrapped with insulating paper. This insulated conductor is then further thermally insulated with high-density pressboard, such as would be employed in a power transformer. The insulated conductor is then suspended in the transformer liquid, for which the temperature is controlled independently by means of bulk oil heater. Thus, the bulk oil heater is used to control the selected temperature for the specific time of exposure. A pressboard barrier is added to the cell to allow for natural convection of oil flow around the hot conductor, simulating what would happen in an ONAN cooled power transformer. In this test cell the insulated conductor and associated turn spacer insulation can be controlled at one temperature while the oil and its associated barrier-type insulation can be controlled at a prespecified temperature. The proposed test cell is designed separately for low-temperature and high-temperature operations. Sectional and internal views of the low-temperature cell are shown in Figures 1 and 2, respectively, whereas in the case of the high-temperature cell it is shown in Figures 3 and 4, respectively. The test system consists of the following parts, as labeled in Figures 5a and 5b.

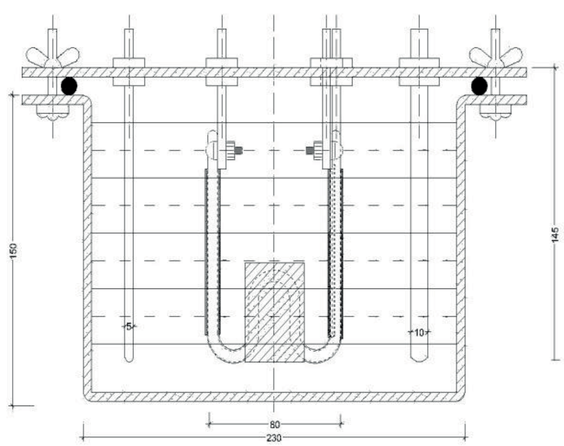

Figure 1. Low-temperature cell.

Figure 2. Internal view of low-temperature cell.

1.1.1. Aging cell

To make the test cell reasonably realistic, material and volume ratios of the substation transformers and test cell are selected to match as closely as possible as per standard IEC-62332. The copper conductor for the test cell is taken from the original winding of a 66-kVA transformer. The crepe paper/kraft paper 5 mil/ kraft paper 2 mil is wrapped around the current-carrying copper conductor, suspended in the test cell, as shown in Figures 1–4. The dimensions of the copper conductor in mm are shown in Figure 6.

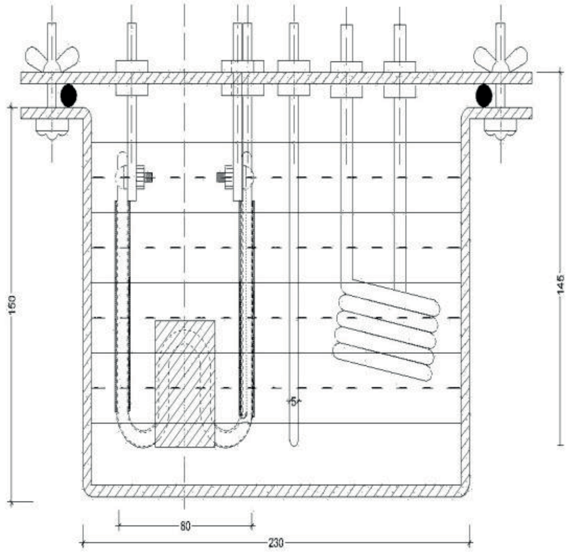

Figure 3. High-temperature cell.

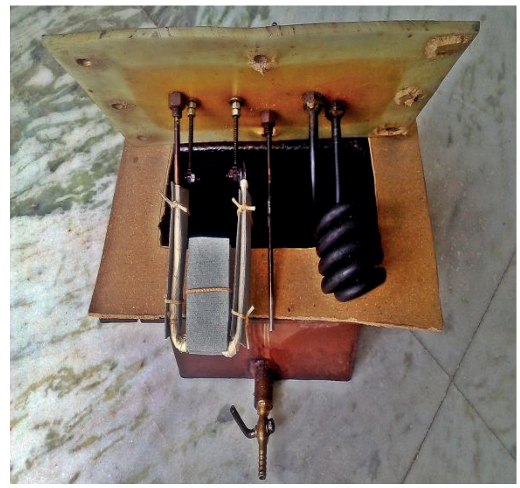

Figure 4. Internal view of high-temperature cell.

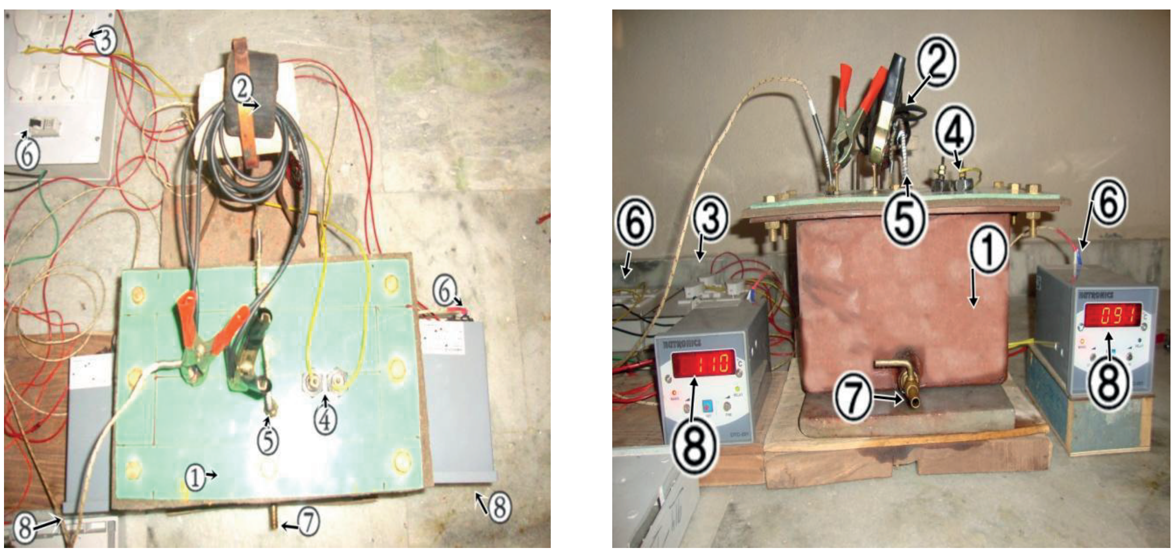

Figure 5a. a) Top view of working test cell. b) Front view of working test cell.

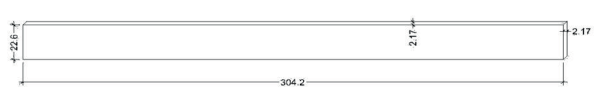

Figure 6. Copper conductor.

Length = 304.2 mm, breadth = 9.22 mm, and thickness = 2.17 mm.

Conductor surface area:

$$= 2\ (\text{length} \times \text{breadth} + \text{breadth} \times \text{thickness} + \text{thickness} \times \text{length}),$$

$$= 2\ (30.42 \times 0.922 + 0.922 \times 0.217 + 0.217 \times 30.42) = 69.7\ \text{cm}^2.$$

Paper and pressboard volume:

$$= [\text{breadth} \times \text{thickness} \times \text{length}] + [\{\text{breadth} \times \text{thickness} \times \text{length}\} + \{\text{breadth} \times \text{thickness} \times \text{length}\}],$$

$$= [3.5 \times 0.0125 \times 40 \times 60] + [\{5.5 \times 0.16 \times 15\} + \{3.5 \times 0.16 \times 30\}],$$

$$= [\{105\} + \{13.2 + 16.8\}] = 135 \text{ cm}^3 = 0.135 \text{ in } 1000 \text{ cm}^3 \text{ units.}$$

Mineral oil = 3.27 L.

1.1.2. Toroidal current transformer

A small current toroidal transformer mounted on the top of the cell supplies the required current to the copper conductor, thus heating it to the desired temperature. It consists of a “high-turns” winding, which functions as the primary winding. The secondary winding of the toroidal transformer consists of a high-current insulated copper conductor. The number of turns of the secondary winding can be varied by the operator depending upon the specified temperature level requirement. The two ends of this high-current wire, which works as the secondary winding, are connected to the copper conductor of the test cell during experimentation, shown as part 2 in Figures 5a and 5b.

1.1.3. Power supply

A single-phase 230-V, 50-Hz supply is connected to the heater and temperature controllers 1 and 2. An MCB switch is also provided for protection from short circuits, shown as part 3 in Figures 5a and 5b.

1.1.4. Immersion heater

For low temperature 100-W heaters and for high temperature 500-W heaters are used. The immersion heaters are operated at an AC supply of 230 V and 50 Hz, shown as part 4 in Figures 5a and 5b.

1.1.5. Control system

Automatic monitoring with thermal sensors controls the temperatures of the test object and liquid. The temperature controller feedback circuit is used to maintain each temperature within ± 1 K. The temperature controller terminals and relay connections are shown as parts 5 and 6 in Figures 5a and 5b.

1.1.6. Safety system

In order to ensure safe operation of the test cell under rising temperatures, a tripping device is provided, which automatically switches off the power supply if the temperature exceeds the limiting value, shown as part 6 in Figures 5a and 5b.

1.1.7. Sampling system

In the sampling system, a separate outlet is provided at the bottom of the test cell for the collection of oil samples, shown as part 7 in Figures 5a and 5b. The paper samples at different temperatures are collected after lifting the cover plate from the top of the test cell.

1.1.8. Monitoring/data collection system

Two temperature controllers and two K-type thermocouples are installed securely for measurement and control of oil as well as conductor or winding temperature. These controllers continuously record the reading of the proposed cell, shown as part 8 in Figures 5a and 5b.

2. Results and discussion

The aging status of the transformer can be known by the condition of the mineral oil and cellulose. Oil condition can be assessed by different types of tests such as acidity, interfacial tension, furan contents, water contents, breakdown voltage, viscosity, and flash point. On the other hand, paper condition is best judged by mechanical strength, which can only be measured directly after transformers are scrapped. However, this process is not feasible because during the scrap process a transformer goes through different wear and tear stages. In this work, a new dual test model is developed and designed for solid insulation samples as already discussed. There are two types of tests that can be used to determine the mechanical strength of paper as well as pressboard: degree of polymerization (DP) and tensile strength (TS). TS represents the true strength while DP is regarded as an expressive strength measurement. Both methods can be used as a criterion to estimate the useful end-of-life of oil-filled transformers.

DP is a diagnostic tool to assess the condition of paper insulation. It provides information regarding the aging of insulation. A DP value of 1200 indicates that the paper is in good condition and a DP value of 200 indicates that the condition of the paper has deteriorated [4]. Figures 7–9 respectively show the variation of DP of crepe paper, kraft paper 5 mil, and kraft paper 2 mil in the presence of oil and pressboard at different temperatures and time durations extended to 500 h. The study shows that aging was slow for temperatures of 60 °C and 70 °C and curves reflect less variation [5]. With further increase in oil temperature the oil degrades fast and the DP start decreasing with temperature.

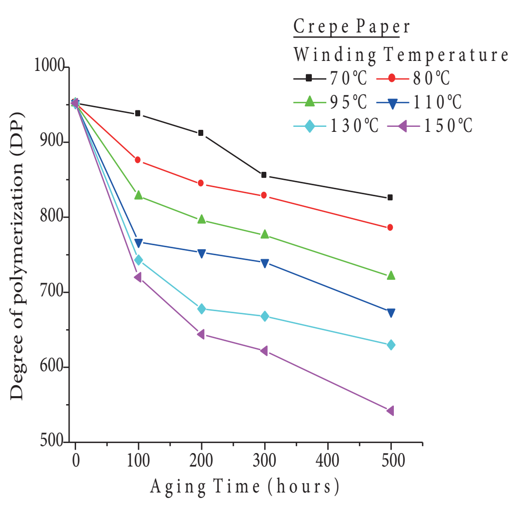

Figure 7. Variation of DP of crepe paper for time span of 500 h at temperatures as listed in block.

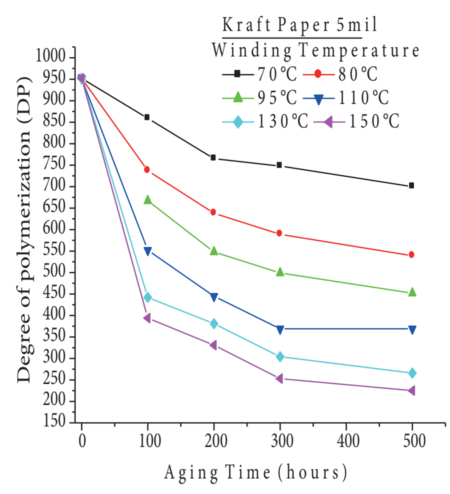

Figure 8. Variation of DP of kraft paper 5 mil for time span of 500 h at temperatures as listed in block.

The decreasing pattern of DP is shown in Figure 10 in the presence of crepe paper, kraft paper 5 mil, and kraft paper 2 mil reflects a nonlinear relationship with aging time. This decreasing trend is caused by oxidation, chemical defects, and increasing fiber particles [6].

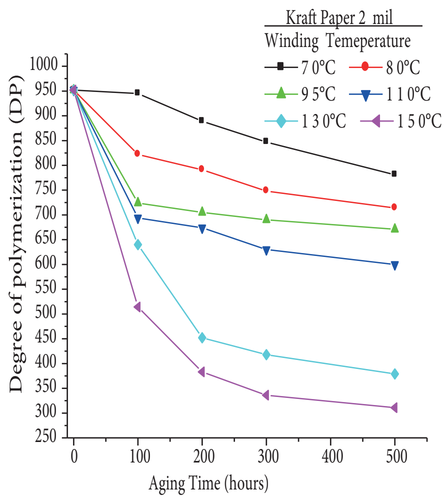

Figure 9. Variation of DP of kraft paper 2 mil for time span of 500 h at temperatures as listed in block.

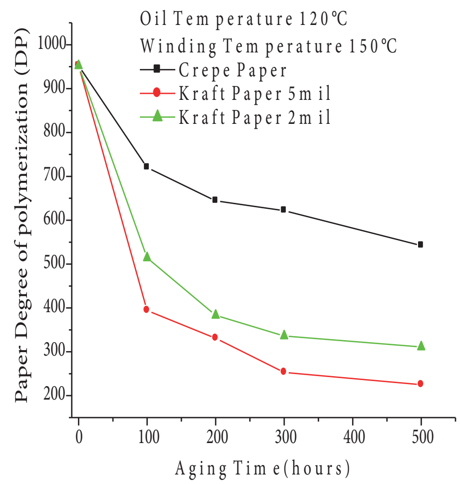

Figure 10. Comparison of DP of crepe paper, kraft paper 5 mil, and kraft paper 2 mil in the presence of oil and pressboard for a span of 500 h at temperatures as listed in block.

The mechanical strength of paper is calculated by TS, which is the breaking strength per unit cross-section area of paper. It is necessary to measure the strength of paper and provide an indication of the suitability of insulation used for a particular environment and utility. Figures 11–13 respectively show the variation of TS of crepe paper, kraft paper 5 mil, and kraft paper 2 mil in the presence of oil and pressboard at different temperatures for time durations extended to 500 h.

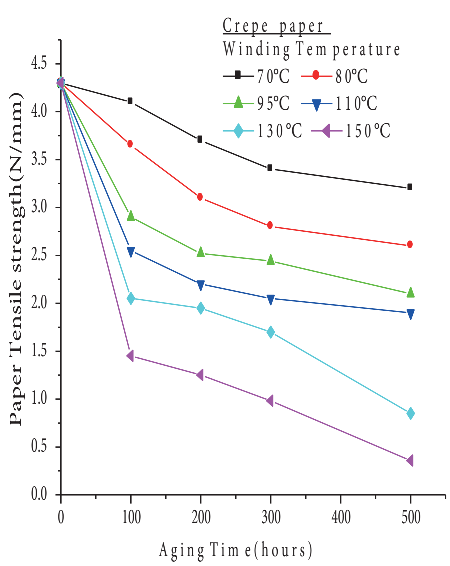

Figure 11. Variation of TS of crepe paper for time span of 500 h at temperatures as listed in block.

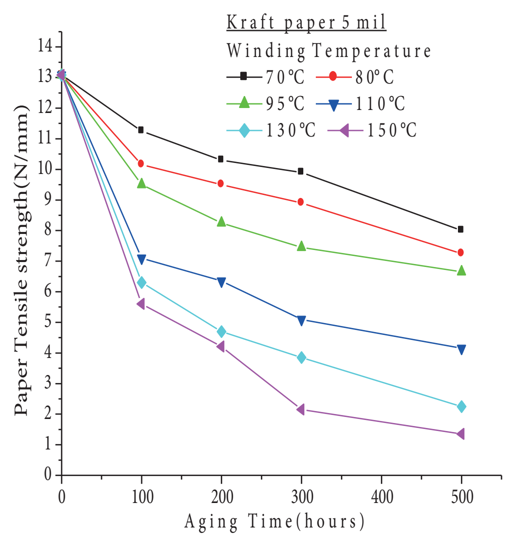

Figure 12. Variation of TS of kraft paper 5 mil for time span of 500 h at temperatures as listed in block.

The decreasing pattern of TS shown in Figure 14 in the presence of crepe paper, kraft paper 5 mil, and kraft paper 2 mil also reflects a nonlinear relationship with aging time. This decreasing trend is due to increasing or widening of microcracks in the enormously heterogeneous paper that finally leads to catastrophic failure of the system [7,8].

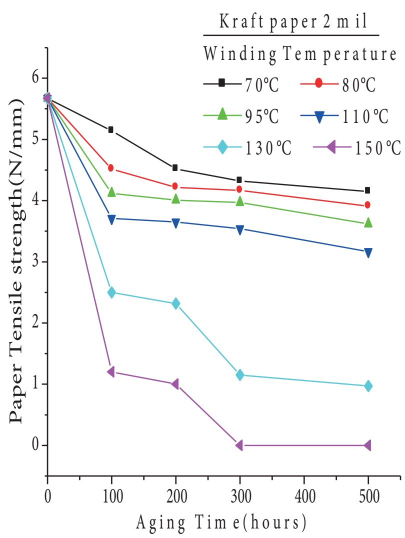

Figure 13. Variation of TS of kraft paper 2 mil for time span of 500 h at temperatures as listed in block.

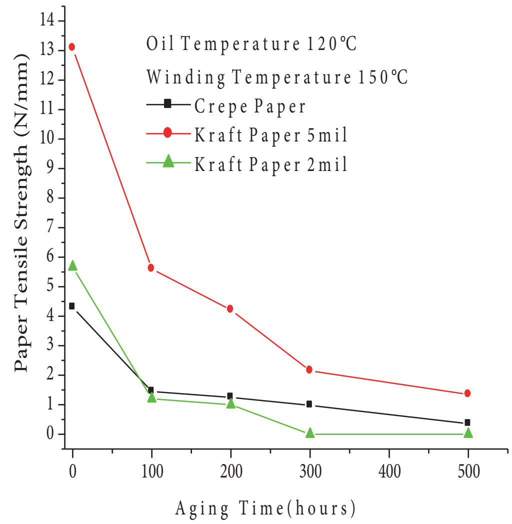

Figure 14. Comparison of TS of crepe paper, kraft paper 5 mil, and kraft paper 2 mil in the presence of oil and pressboard for a span of 500 h at temperatures as listed in block.

The breakdown strength measurement needs to be done to check the reliability of the paper insulation. The purpose of this test is to determine the limit at which the paper withstands the applied voltage. In Figure 15 the breakdown voltage of crepe paper, kraft paper 5 mil, and kraft paper 2 mil shows an increasing trend because, as the paper ages, the density of paper increases and results in higher breakdown voltage. Mechanical strength of paper broadly has no effect on breakdown voltage; mostly it depends upon the density of the paper [9].

Figure 16 shows a comparison of the breakdown voltage of pressboard in the presence of different insulating paper and oil. The pressboard becomes brittle due to extreme temperature and its strength drops drastically

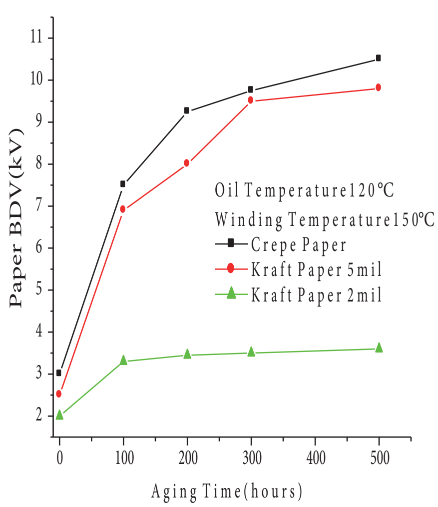

Figure 15. Comparison of BDV of crepe paper, kraft paper 5 mil, and kraft paper 2 mil in the presence of oil and pressboard for a span of 500 h at temperatures as listed in block.

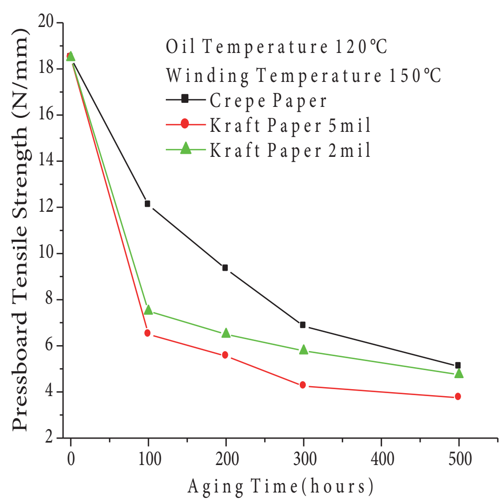

Figure 16. Comparison of pressboard TS in presence of oil and crepe paper, kraft paper 5 mil, and kraft paper 2 mil for a span of 500 h at temperatures as listed in block.

with aging. The strength mostly depends upon the structure of the fiber. At high temperatures cracks appear in fibers, leading to failure.

It is observed that a reduction in mechanical strength due to aging has no relationship with breakdown voltages of pressboard. However, pressboard density and oil condition can influence the dielectric strength of pressboard. The increasing trends are caused by the increase in density of aged pressboard samples, as shown in Figure 17.

3. Comparison analysis

The graphical comparison and correlations between DP, TS, and furan content are presented in this section.

Figures 18–20 respectively show a good correlation between DP and TS of paper in the case of crepe paper, kraft paper 5 mil, and kraft paper 2 mil. The strength of paper critically depends on the DP of cellulose. It drops in direct proportion to DP.

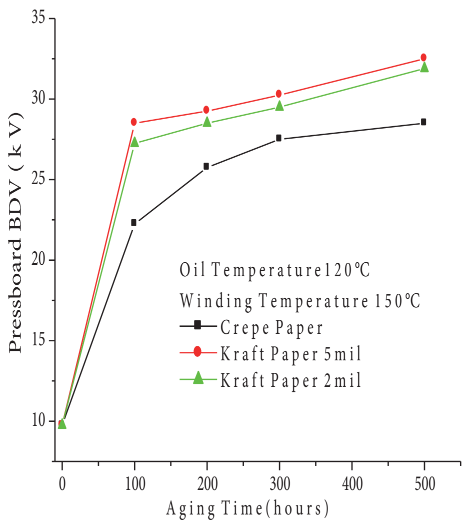

Figure 17. Comparison of pressboard BDV in presence of oil and crepe paper, kraft paper 5 mil, and kraft paper 2 mil for a span of 500 h at temperatures as listed in block.

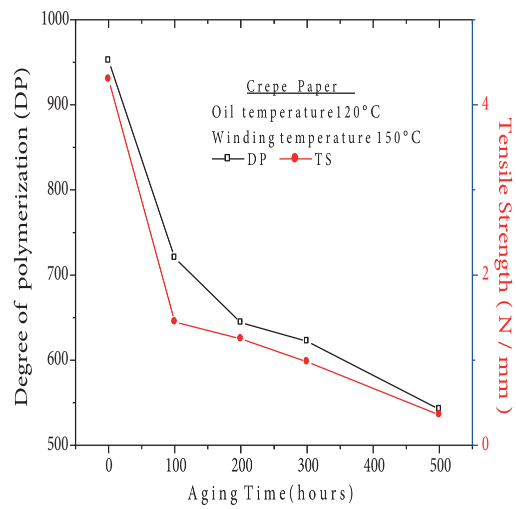

Figure 18. Comparisons between DP and TS of crepe paper for time span of 500 h at temperatures as listed in block.

A comparison of the furan content and DP is carried out in Figures 21–23 respectively for crepe paper, kraft paper 5 mil, and kraft paper 2 mil. The increase in concentration of furan content highlights degradation and the condition of the paper in terms of DP, because the rate of change of furan concentration indicates the rate of aging of paper. If furan content is high, the DP value will be truncated at that particular temperature, and vice versa. The main advantage of using furan analysis as a diagnostic tool is that the compounds or byproducts produced are specific to paper as they cannot be produced by oil.

4. Correlation analysis

Graphical analysis can be enhanced by validation with correlation analysis. The correlation coefficient is a numerical measure of the strength of the relationship between two random variables. There are many coefficients that are appropriate to use under different circumstances. Among them, Pearson's product moment correlation coefficient is the most frequently utilized. Pearson's product moment correlation coefficient measures the linear relations between two variables. It considers a series of n measurements of X and Y written as x_i and y_i with

$i = 1, 2, \ldots\ldots, n$ and so sample correlation coefficient r_{xy} can be calculated as:

$$r_{xy} = \frac{\sum_{i=1}^{n} (x_i - \overline{x})(y_i - \overline{y})}{(n-1)\ S_x S_y}, \tag{1}$$

where $\overline{x}$ and $\overline{y}$ are the sample means of X and Y and S_x and S_y are sample standard deviations of X and Y.

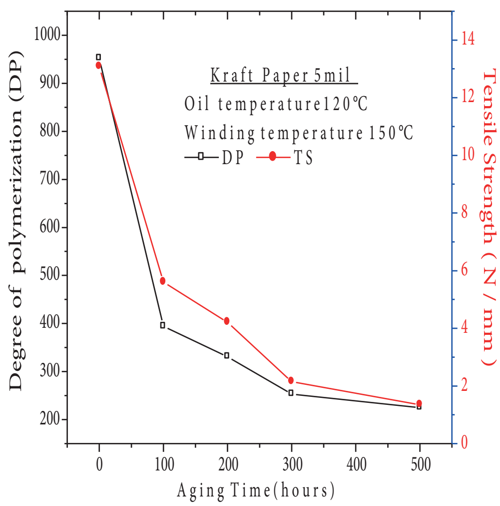

Figure 19. Comparisons between DP and TS of kraft paper 5 mil for time span of 500 h at temperatures as listed in block.

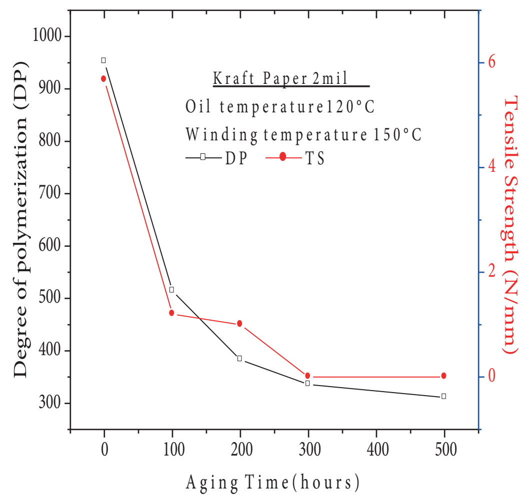

Figure 20. Comparisons between DP and TS of kraft paper 2 mil for time span of 500 h at temperatures as listed in block.

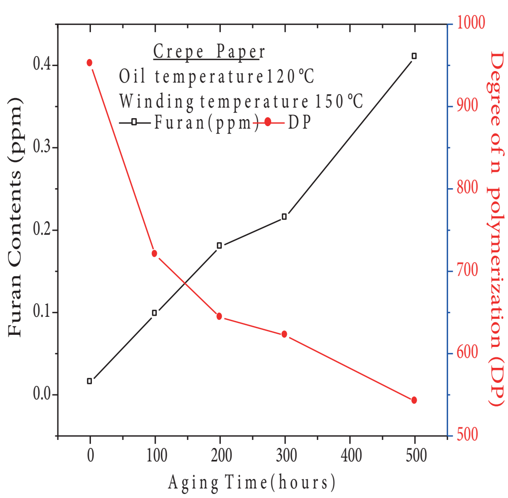

Figure 21. Comparisons between DP and furan of crepe paper for time span of 500 h at temperatures as listed in block.

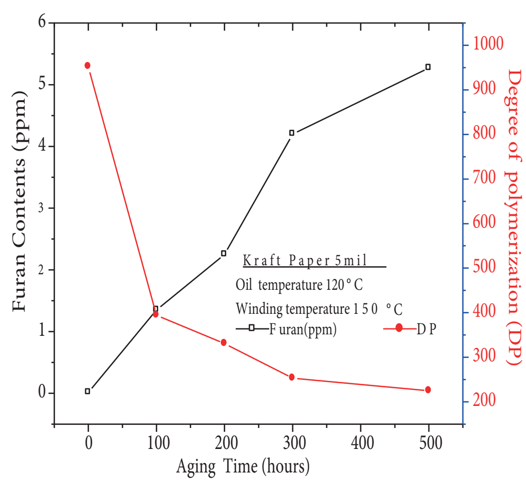

Figure 22. Comparisons between DP and furan of kraft paper 5 mil for time span of 500 h at temperatures as listed in block.

The value of the correlation coefficient varies from –1 to 1. A positive value means the two variables are positively correlated, that is, the two variables vary in the same direction; a negative value indicates their negative correlation. A value close to +1 or –1 reveals that the two variables are highly related, whereas a 0 value indicates no correlation. The general correlation category is shown in Table 1. The relationship between two properties can be tested by correlating them with each other. The correlation coefficient determines the apparent connection between various properties of solid insulation.

Table 1. General correlation category.

SN	Correlation coefficient (r)	Correlation category
1	0.0–0.4	Weak correlation
2	0.5–0.7	Moderate correlation
3	0.7–0.9	Strong correlation
4	0.9–1.0	Very Strong correlation

The linear correlations between the DP and TS of crepe paper, kraft paper 5 mil, and kraft paper 2 mil in the presence of oil and pressboard at oil temperature 120 °C and winding temperature 150 °C for aging duration of 500 h are as shown in Figures 24–26, respectively.

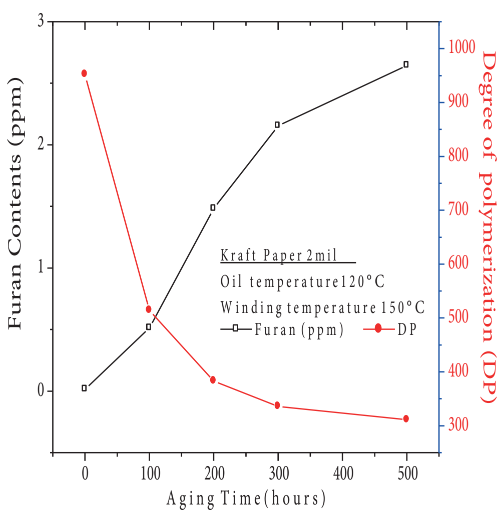

Figure 23. Comparisons between DP and furan of kraft paper 2 mil for time span of 500 h at temperatures as listed in block.

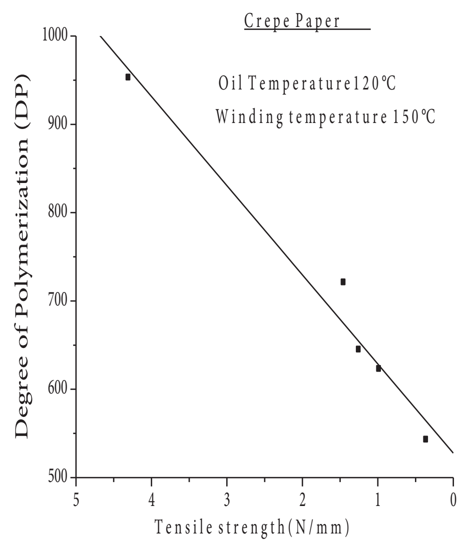

Figure 24. Correlation between DP and TS of crepe paper for time span of 500 h at temperatures as listed in block.

The mathematical model and correlation coefficient between the DP and TS of crepe paper, kraft paper 5 mil, and kraft paper 2 mil are presented below. Measurement of the DP over a range of TS enables us to construct Arrhenius plots. Activation energy (Ea) and process constant (A) are calculated using experimental data in ORIGIN 6.0 [10] and ORIGIN 8.0 [11] software for linear fit regression analysis. The Arrhenius equation make use of temperature in Kelvin, whereas the value of the gas constant (Rg) is 8.314 J/mole K. The values of Ea and A are employed to estimate the lifetime of oil-immersed transformers [12]. Analysis is performed for experimental data of crepe paper, kraft paper 5 mil, and kraft paper 2 mil. The fundamental goal is to determine the curve that best fits the data.

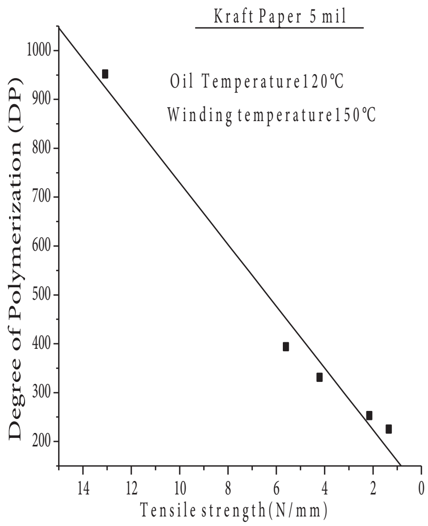

Figure 25. Correlation between DP and TS of kraft paper 5 mil for time span of 500 h at temperatures as listed in block.

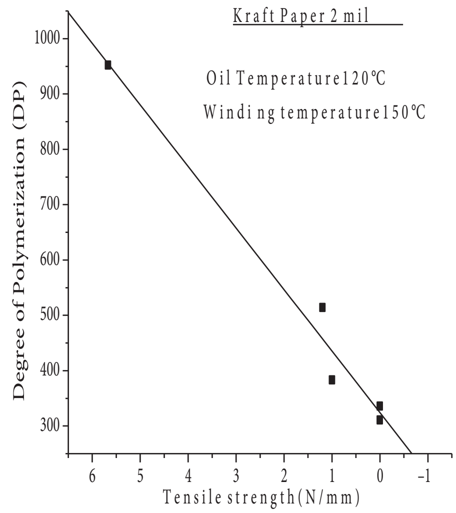

Figure 26. Correlation between DP and TS of kraft paper 2 mil for time span of 500 h at temperatures as listed in block.

The 'Fit Linear' dialog box is utilized to perform linear regression and fits a straight line to a given dataset (x_i, y_i), i = 1, 2,... n comprising x as the independent variable and y as the dependent variable. The linear regression fits the data to a model of the following form:

$$Y = \beta_0 + \beta_1 X + \varepsilon, \tag{2}$$

where β_0 is the y intercept, β_1 is the slope, and ε is the error term. The error term represents the unexplained variation in the dependent variable and is usually assumed to have a mean of zero. In Figures 24–26 respectively, the x-axis represents TS and the y-axis represents DP.

If X represents TS and Y represents DP then linear regression fits the data in Eqs. (3), (4), and (5) with respect to crepe paper, kraft paper 5 mil, and kraft paper 2 mil, respectively.

Crepe paper:

$$Y = 527.64 + 100.95X \tag{3}$$

R^2 = 0.971; activation energy = 0.839 kJ/mole; A = 6.28 $\times$ 10^{42}

Correlation coefficient = 0.985

Kraft paper 5 mil:

$$Y = 97.023 + 63.27X \tag{4}$$

R^2 = 0.979; activation energy = 0.526 kJ/mole; A = 6.28 $\times$ 10^{27}

Correlation coefficient = 0.989

Kraft paper 2 mil:

$$Y = 324.09 + 111.22X \tag{5}$$

R^2 = 0.977; activation energy = 0.924 kJ/mole; A = 1.96 $\times$ 10^{48}

Correlation coefficient = 0.988

The value of the correlation coefficient for crepe paper, kraft paper 5 mil, and kraft paper 2 mil as shown in Figures 24–26 indicates a very strong correlation between DP and TS. The coefficient of determination (R^2)

is found to be 97.14% for crepe paper, 97.95% for kraft paper 5 mil, and 97.77% for kraft paper 2 mil. This analysis will be extended to all properties discussed later and the values of the correlation coefficient, activation energy, and coefficient of determination (R^2) for paper and pressboard are tabulated in Tables 2 and 3.

Table 2. Correlation coefficient, activation energy, and coefficient of determination (R^2) for pressboard.

Sn.	Correlation analysis between	Insulation paper	R^2 (linear regression)	Activation energy (KJ/mol)	r (correlation coefficient)	Correlation category (negative)
1	Pressboard TS and BDV	CP	0.95	0.012	−0.97	Very strong correlation
		KP 5 mil	0.99	0.013	−0.99	Very strong correlation
		KP2 mil	0.99	0.013	−0.99	Very strong correlation

Table 3. Correlation coefficient, activation energy, and coefficient of determination (R^2) for paper.

Sn.	Correlation analysis between	Insulation paper	R^2 (linear regression)	Activation energy (KJ/mol)	r (correlation coefficient)	Correlation category (negative)
1	Paper DP and furan content	CP	0.95	0.448	−0.97	Very strong correlation
		KP 5 mil	0.97	0.351	−0.98	Very strong correlation
		KP 2 mil	0.96	0.951	−0.97	Very strong correlation
2	Paper DP and BDV	CP	0.98	0.042	−0.99	Very strong correlation
		KP 5 mil	0.96	0.827	−0.98	Very strong correlation
		KP 2 mil	0.98	0.328	−0.98	Very strong correlation
3	Paper TS and BDV	CP	0.96	0.016	−0.98	Very strong correlation
		KP 5 mil	0.99	0.005	−0.99	Very strong correlation
		KP 2 mil	0.98	0.002	−0.99	Very strong correlation

5. Expected paper insulation lifetime

The test results as shown in Figures 11–13 respectively show that TS depends not only on the aging time of oil but also on aging temperatures. One of the important mechanical parameters for cellulose insulation in oil-immersed transformers is TS, whose failure causes a short circuit [4]. The Arrhenius law is an exponential, mathematical law that is dependent on the temperature effect on chemical reaction rates. In 1889, Arrhenius showed that the relationship between temperature and the rate constant for a reaction obeyed the following equation:

$$k = Ae^{\frac{-E_a}{RT}}. \tag{6}$$

Now assume that the life of the product is proportional to the inverse of the rate of reaction, and the Arrhenius life relation is given by:

$$t = Be^{\frac{E_a}{RT}}. \tag{7}$$

In Eqs. (6) and (7) Ea, R, and T are the activation energy, gas constant, and temperature (K), respectively, whereas A and B are constant factors. The variation of the logarithm of a lifetime with the reciprocal temperature (K^{-1}) is shown in Figure 27.

In this work the expected paper insulation lifetime curve is plotted for crepe paper, kraft paper 5 mil, and kraft paper 2 mil respectively by using Eq. (7) at an oil temperature of 120 °C and winding temperature of 150 °C. The results of this work supported the relationship between log 2-FAL and DP in the presence of kraft paper 5 mil and found a strong correlation of 2-FAL with DP as shown in Figure 28. The expected lifetime estimated in this work bears a linear relationship with respect to $1/T$ and is similar to the one reported based on the studies conducted by Wicks from DuPont and Prevost from Weidmann [13,14]. There is no simple and unique end-of-life criterion that can be used to quantify the remaining life of oil-immersed transformers. However, these expected lifetime curves are useful to focus on aging processes and the condition of transformer insulation.

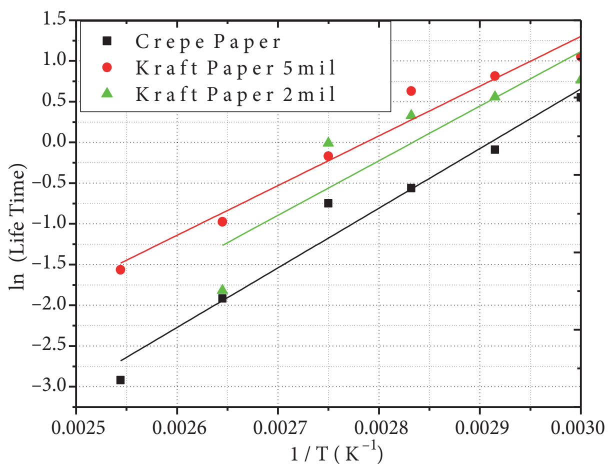

Figure 27. Arrhenius life plot of tensile retention at 423 K.

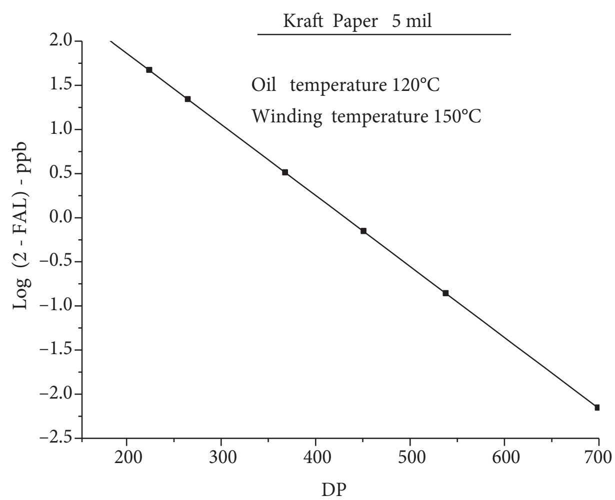

Figure 28. Log 2-FAL versus DP for kraft paper 5 mil.

6. Conclusion

In this work an experimental investigation is reported on the thermal aging of paper and pressboard at an oil temperature of 120 °C and winding temperature of 150 °C for time durations extended to 500 h.

The correlation coefficients between DP and TS are 0.985, 0.989, and 0.988 for crepe paper, kraft paper 5 mil, and kraft paper 2 mil, respectively, and these show very strong correlations between DP and TS.

The coefficient of determination (R^2) is found to be 0.971, 0.979, and 0.977 for crepe paper, kraft paper 5 mil, and kraft paper 2 mil, respectively. R^2 measures the percentage of variation in the dependent variable, which is explained by the independent variable. In this work the value of R^2 is close to 1 for crepe paper, kraft paper 5 mil, and kraft paper 2 mil and indicates better fit of the data, which in turn implies greater explanatory power of the estimated regression equation and therefore better prediction of the dependent variable.

The correlation coefficient between DP and TS is 0.989, and it being near to one reflects strong correlation. The coefficient of determination is found to be 0.979 in the case of kraft paper 5 mil, which shows a better degree of fitness of data as compared to crepe paper and kraft paper 2 mil. It can be concluded that kraft paper 5 mil has better tensile retention than kraft paper 2 mil and crepe paper.

The color of crepe paper, kraft paper 5 mil, kraft paper 2 mil, and pressboard changed from the original light brown shade to dark brown with aging.

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