Aging of Pressboard in Different Insulating Liquids

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Abstract— **Today, the transformer industry uses alternative insulating liquids more and more. Possible alternatives are vegetable esters such as rape seed, soy bean or sunflower oils or synthetic esters. The aim is to replace the flammable and environmentally harmful mineral oils. Another advantage of these liquids is the higher water solubility, which is claimed to be responsible for a reduced aging rate of cellulosic insulation compared to mineral oil.**

In a comprehensive aging experiment 3 mm thick, high density pressboard was aged side by side in nine different insulating liquids; four vegetable oils, one synthetic ester, one isoparaffinic and three naphthenic mineral oils. The materials were aged at 120, 135 and 150°C for up to twelve months in vessels with open, as well as with closed, expansion systems. To simulate the load cycles in a real transformer, the oil was cooled to about 80°C for two hours each day.

The effect of the thermal aging on the mechanical, chemical and electrical properties of the pressboard and the different liquids are discussed.

I. INTRODUCTION

In the recent years, the variety of insulating liquids for transformers has increased steadily. The reasons for this increase are manifold:

- The use of inhibited mineral oils is becoming more widely accepted especially in Europe. It is used for decades in North America.
- Mineral oils have been adapted in order to overcome the corrosive sulfur problem.
- Natural and synthetic esters have been introduced for transformers which are located in densely populated areas due to their lower flammability.
- The higher biodegradability of synthetic and natural esters is advantageous when transformers are mounted in environmentally sensitive places.
- Natural esters are based on renewable resources and not dependent on fossil raw materials.

II. INSULATING LIQUIDS

A. Mineral oil

Mineral oil is made from crude oil and consists of a variety of hydrocarbon compounds. The hydrocarbons in transformer oils are mainly paraffinic, naphthenic or aromatic.

The distinction between paraffinic and naphthenic insulating liquids is not sharp. Typically, oils containing less than 50 % carbons in paraffinic structures are defined as naphthenic oils. For a paraffinic oil this value is 56 % and above [1]. In isoparaffinic oils, the molecule is branched; which makes them suitable for the use in cold climates.

B. Ester insulating liquids

Organic esters are chemical compounds derived by reacting carbonic acid with alcohol. Esters are ubiquitous. Many naturally occurring fats and oils are the fatty acid esters of glycerol. Esters with low molecular weight are commonly used as solvents or fragrances.

Esters for use in transformers are reaction products of fatty acids and a polyol. In the case of natural esters glycerol is the naturally occurring polyol. For synthetic esters the polyol is typically pentaerythritol.

The composition of fatty acids depends on the nature of the oil seed [2]. While native soy bean oil has a content of multiple unsaturated fatty acids of more than 60 %, rape seed oil has only about 35 %. For use as an insulating liquid, the composition can be changed by partial hydrogenation. This chemical treatment yields a product which is thermally more stable and less susceptible to oxidation.

III. TEST MATERIALS AND PROCEDURE

A. Materials

High density pressboard, Type 3.1A as per IEC 60641-3-1 was aged in several types of insulating liquids, Table I, at temperatures of 120, 135 and 150 °C. As test specimens, 6 sheets of 380 × 430 × 3 mm were aged.

TABLE I. LIQUIDS FOR AGING TEST

#	Insulating liquid	Type
1	Rapeseed oil	Vegetable ester
2	Soybean oil	
3	Sunflower oil	
4	Rapeseed oil	
5	Pentaerythrit ester	Synthetic ester
6	Isoparaffinic, trace inhibited	Mineral oil
7	Naphtenic, top grade, trace inhibited	
8	Naphtenic, standard grade, non inhibited	
9	Naphtenic, medium grade, inhibited	

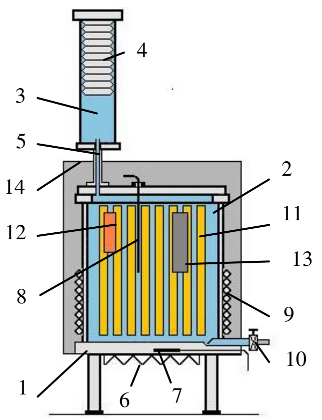
B. Test equipment

The concept underlying the design of the aging vessels and the test procedure was to create conditions similar to those encountered in power transformers. A vessel consisted of nine independent test chambers, which were heated or cooled jointly, Figure 1, [3].

Three aging vessels were operated using the concept of “closed expansion”. In this system, the oil in the expansion tube had no contact with the ambient air. The aging experiment at 120°C was also run in a vessel with an open expansion system. In this system, the oil in the expansion tube was continuously in contact with dry air via a silicagel conservator. The interface between the oil in the expansion tube and the air was 60 cm².

The possible catalytic effect of metals on the aging of the oil / solid insulation was taken into account in that, on the one hand, the sand blasted steel walls of the test chambers (surface: 60 dm²) were intentionally left bare, while on the other hand copper plates with a surface of 3 dm² and core steel with a surface of 6 dm² were placed in each test chamber in addition to the samples.

The operating temperature was recorded and continuously monitored by means of sensors mounted in the center of the chamber. The temperature variation as a function of location and time within and among the nine test chambers of an aging vessel was in the range of ± 1.5 K of the set-point aging temperature. The difference between the temperature in the test chamber and that in the glass tube of the expansion system was 80 to 100 K, depending on the predetermined set-point temperature. This temperature difference would have caused a continuous oil circulation, which was deliberately reduced by means of flow baffles between the test chamber and the expansion tube.



1: Aging vessel with nine test chambers
2: Test chamber (volume: 20 dm³)
3: Glass expansion tube
4: Steel bellow
5: Flow baffle
6: Heater
7: Temperature control
8: Temperature measurement
9: Cooling coils
10: Outlet valve
11: Test specimens
12: Copper sheet
13: Core steel; surface
14: Thermal insulation

Figure 1. Aging vessel, sectional view of one test chamber

C. Test procedure

The test specimens were dried at 105 °C for 24 h in an oven with forced air circulation and subsequently in a vacuum oven at 105 °C and < 1 mbar for 48 h. The dried test specimens were placed in the aging chambers and the chambers were heated to 90 °C and evacuated to a pressure of < 1 mbar. After 4 h the chambers were filled with the insulating liquid. In this process the liquids were partly degassed. The remaining oxygen concentration was in the range of 1000 to 5000 ppm. For the evaluation of the material properties before aging, one set of test specimens was treated only until this stage. After draining the oil, this material was removed and tested; test values are reported as “initial” in this paper.

The effect of repeated load cycles of a power transformer was simulated. A 24 hour temperature cycle consisted of 19 h nominal temperature, 2 h cooling (during this phase the temperature in the test chamber dropped to 70, 80 and 90°C respectively) and 3 h heating, temperature increasing back to nominal.

After the designated aging duration, the oil temperature was reduced to 60 °C and kept for 24 h before opening the chamber and removing the material. The liquids for the tests were sampled in glass bottles. The pressboard sheets were wrapped in plastic film and stored at 23°C until testing.

TABLE II. NOMINAL TEMPERATURES AND AGING DURATION

Temperature	Expansion	Duration
120 °C	Open	2, 4 and 8 months
120 °C	Closed	3, 6 and 12 months
135 °C	Closed	2, 4 and 8 months
150 °C	Closed	1, 2 and 4 months

For each time and temperature combination, Table II, an individual test series was made, i.e. after the test vessel had been filled with liquid, it was not opened until the test was finished. After completion of a test, the chambers were cleaned carefully and the next test was started.

TABLE III. TESTS ON SOLID AND LIQUID INSULATION

Pressboard		Liquids	
Degree of polymerization	IEC 60450	Water content	IEC 60819
Tensile strength	ISO 1924	Relative humidity	
Resistivity/Conductivity	IEC 60093	Acid number	IEC 60212
		Electrical strength	IEC 60156

IV. TEST RESULTS

A. General observations

Because the aging vessels were not opened during the course of the aging experiment, the monitoring of the aging could only be done by a visual inspection of the expansion system. There it was possible to observe gassing, discoloration or other changes of the liquids.

In the four mineral oil chambers more water from the deterioration was formed than the oils could dissolve. In the case of oils 6, 7 and 8, the water had condensed in the cooler expansion system. In the case of oil 9, the water formed an emulsion with the oil.

B. Water content in liquids

For the experiment 8 months aging at 135°C, the water content of the oil was measured weekly, Figure 2. The oil sample was taken from the centre of the chamber with a glass syringe. The sampling was made at the nominal temperature one hour prior the start of the cooling cycle.

The water contents of the three natural esters as well as that of the four mineral oils were at all sampling points very close together, so that the values were averaged for Figure 2.

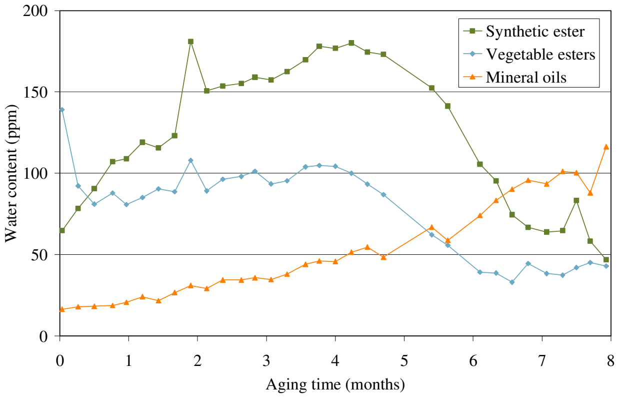


Figure 2. Average water content of insulating liquids; 135°C, closed expansion system, 8 months

The water content of the mineral oils increased steadily throughout the experiment. The water content of the esters also increased in the beginning. After four months it started to decrease again. This effect was observed again in an additional experiment (still running) with an aging temperature of 150°C and closed expansion system. This time, the decrease occured already after 1½ months.

C. *Solid insulation*

The main indicators to assess the aging status of the solid insulating material are tensile strength and degree of polymerization (DP). When the tensile strength deteriorates too much due to thermal stresses, the insulating material can no longer withstand the mechanical stresses that occur in case of a short circuit event.

In the rare case of paper samples being available from the windings, their physical condition is such that tensile strength measurements are questionable; however the DP i.e. the average chain length of the cellulose macro molecule can be taken as a good measure for the aging status of transformer insulation.

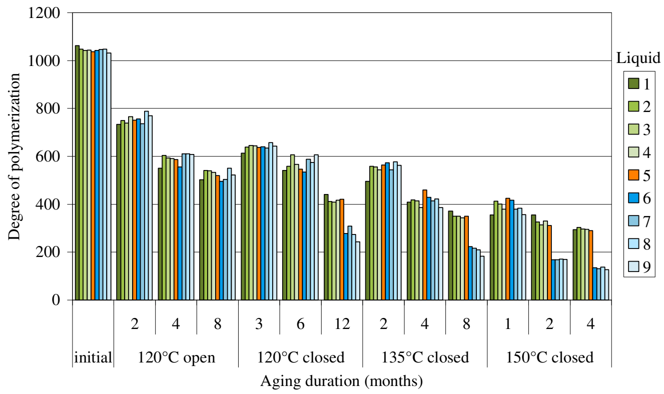


Figure 3[1]. Degree of polymerization of pressboard

[1]Explanation for Figure 3 - Figure 10, liquids as per Table I

Liquids 1 - 4	Vegetable esters
Liquid 5	Synthetic ester
Liquids 6 - 9	Mineral oils

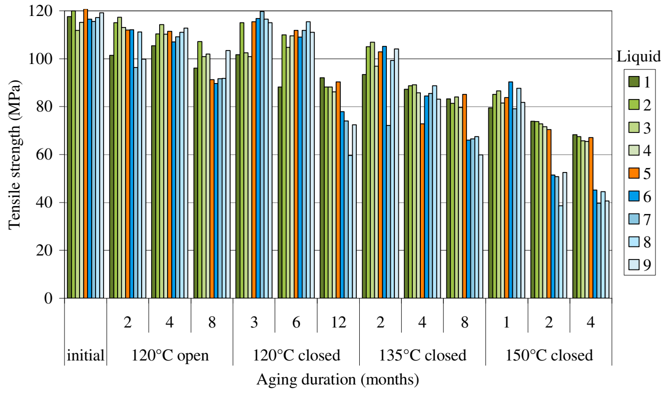


Figure 4. Tensile strength of pressboard

For the experiments of shorter duration, Figure 3 and Figure 4 show that the decrease of tensile strength and DP of pressboard was in the same range when aged in mineral oil as in ester liquids. Only the experiments with long times and/or high temperatures yielded a distinctly faster degradation in mineral oil. A clear correlation between the reduced aging rate and the reduction in water content, as shown in Figure 2, in the esters was found. At this point a large increase in the pressboard water content was observed in the mineral oils, as shown in Figure 5. In the ester fluids this increase did not occur. This is thought to be due to the consumption of water by hydrolysis of the ester molecule.

Water and organic acids are byproducts of the thermal degradation of the solid as well as of the liquid insulation. Due to their polar nature, both compounds are not only dissolved in the liquid, but are also present in the solid insulation. The partitions between solid and liquid are very different for esters and mineral oils. In addition, they are not only temperature dependent, but are also changing with the aging status of liquid and pressboard.

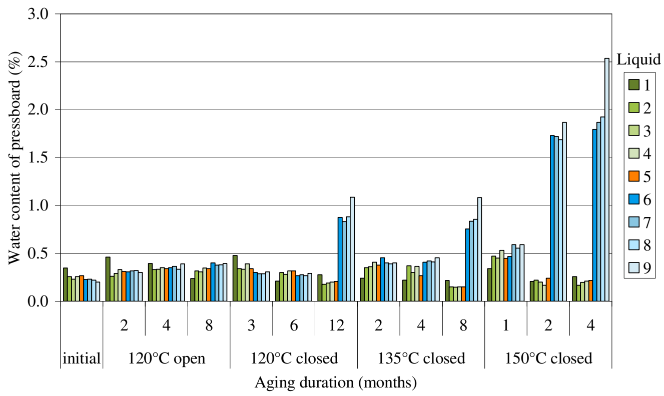


Figure 5. Water content of pressboard

The dielectric properties are indicators of the change of the insulating system due to the formation of conductive ionic compounds. The breakdown strength of pressboard was not measured, as this value is far less sensitive to aging than conductivity.

In Figure 6 the increase of the conductivity is shown. It correlates very well with the increase of the water content of the pressboard.

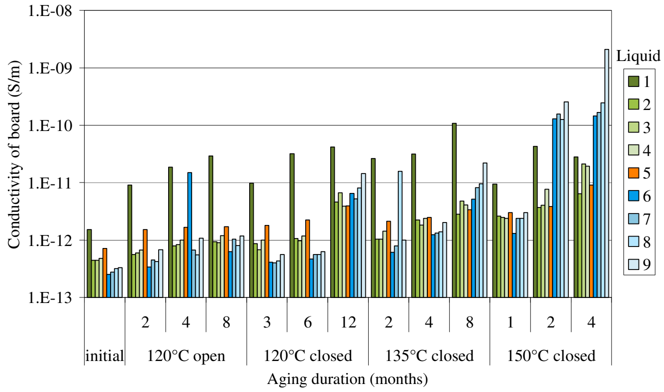


Figure 6. Conductivity of pressboard

D. *Liquid insulation*

The water content of the liquids depicted in Figure 7 exhibited the expected increase for mineral oils. The water content of the esters also increased in the experiment with open expansion system at 120°C. The experiments with closed expansion system and aging temperatures of 135 and 150°C showed a decrease of the water content after some months. Water is obviously consumed by a chemical reaction, most probably the hydrolysis of the esters as shown in Equation (1).

$$R_1COOR_2 + H_2O \rightarrow R_1COOH + R_2OH \qquad (1)$$

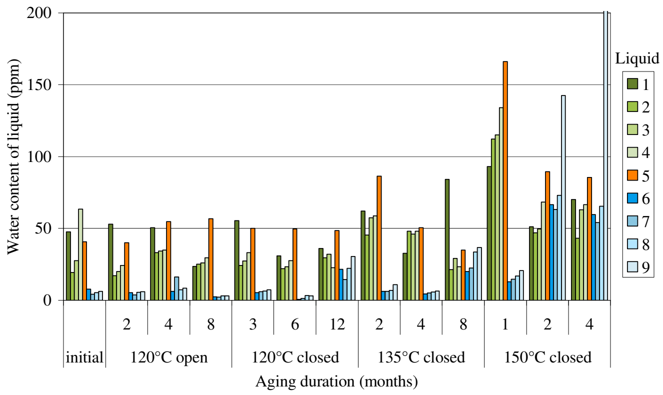


Figure 7. Water content of liquids

One of the very often claimed advantages of ester liquids is their capability to dissolve much higher amounts of water than mineral oils. However, it is the relative humidity, Figure 8 and not the absolute water content that is relevant for the electrical properties of the oil. The relative humidity is calculated as per Equation (2).

$$\text{Relative humidity of oil} = \frac{\text{Water content}}{\text{Saturation water content}} \qquad (2)$$

The amount of water that a liquid can dissolve is not only temperature dependent, but also changes significantly with the aging status [4].

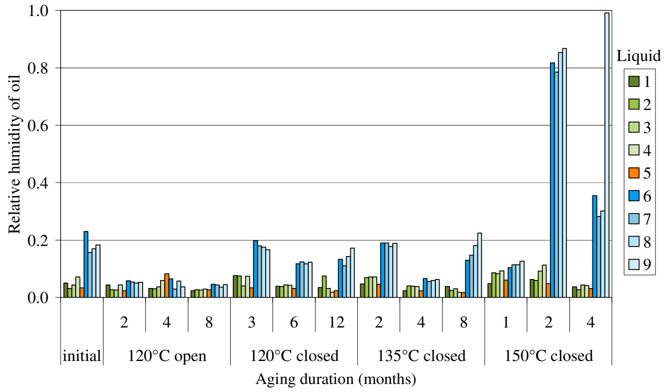


Figure 8. Relative humidity of liquids at 50°C

The electric strength as one of the most important requirements of an insulating liquid is strongly influenced by the amount of free water. In Figure 9 this effect is clearly visible as the breakdown voltage of the mineral oils aged for two and four months at 150° was only about 25% of the initial value.

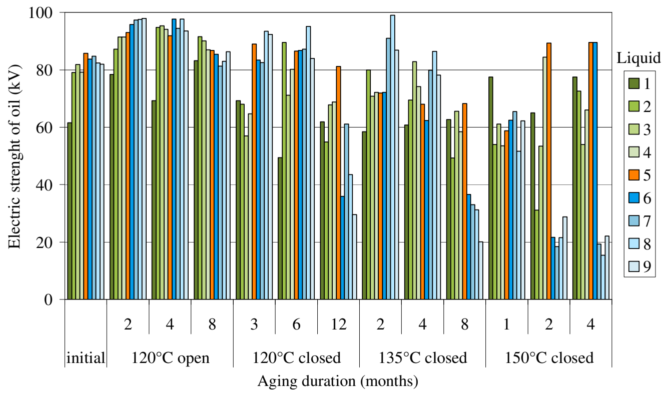


Figure 9. Electric strength of liquids

The acidity of the oil, shown in Figure 10 had no direct influence on the electric strength. The vegetable esters which have by nature a much higher acid number than mineral oils, yielded about the same electric strength as the mineral oils.

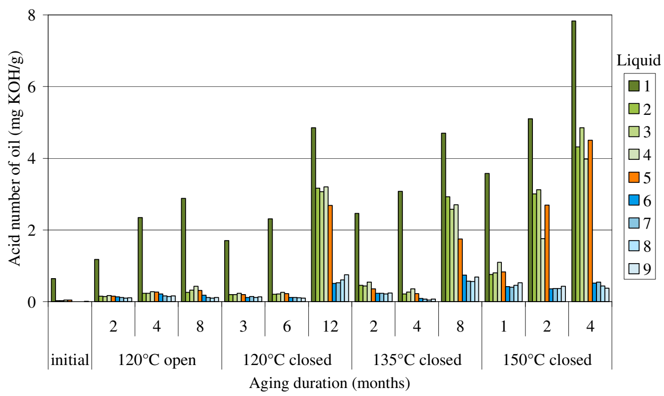


Figure 10. Acid number of liquids

E. *Comparison open and closed expansion system*

Vegetable esters are notorious for their susceptibility to oxidation. To investigate the different aging behaviors with and without oxygen present, the aging at 120°C was run with an open as well as with a closed expansion system. Somewhat surprisingly, none of the tested oil and board properties revealed any significant difference between open and closed expansion system. Whether or not the very small interface between oil and air and its temperature of only about 35°C was the cause of this phenomenon, needs further investigations.

V. SUMMARY AND CONCLUSIONS

High density pressboard was subjected to accelerated aging tests in different vegetable oils, synthetic ester and mineral oils. Findings:

- The initial aging rate of pressboard was the same for ester liquids and mineral oils.
- In the case of ester liquids, reaction with water was observed after a certain aging time, depending on the aging condition. From then on, the pressboard aging rate in ester liquids slowed down markedly.
- At high temperatures and high water concentrations the ester liquids consumed some of the water by hydrolysis, thus preventing the increase of water content in the pressboard and slowing down the deterioration of the cellulose.
- The decrease of rate of cellulose degradation in ester liquids coincided with the instant when the reduction in water content of the esters occured.
- Hydrolysis of esters yield longer chain fatty acids. Further investigation is required to determine whether these acids have detrimental effects on other transformer materials in higher concentrations.
- The high acidity did not have an effect on the aging rate of the pressboard. This confirms results of investigations that found that high molecular acids do not accelerate aging of cellulose [5].
- The quality of the mineral oil, standard grade - high grade; non-inhibited - inhibited, did not reveal substantial differences of the pressboard aging rate.

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REFERENCES

[1] "*Transfomer oil handbook",* Nynas Naphtenics, *2004*

[2] S. Tenbohlen, M. Koch., "Aging performance and moisture solubility of vegetable oils for power transformers", IEEE transactions on power delivery, Vol. 25, Issue 2, 2010, pp. 825-830

[3] H.P. Moser, V. Dahinden, "*Transformerboard II"*, Styrian, second edition, 1999, pp. 137-205

[4] Y. Du et al., "Moisture solubility of differently conditioned transformer oils", IEEE transactions on Dielectrics and Electrical Insulation, Vol. 8, No. 5, 2001, pp. 805-811

[5] L. Lundgaard et al., "Aging of Kraft Paper by Acid Catalyzed Hydrolysis", IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 15, Issue 2, April 2008, pp. 540-546