Analysis of the Chemical and Electrical Characteristic of Vegetable Insulating Oils Exposed to Accelerated Aging

Sun-Ho Choi, and Chang-Su Huh

Abstract— Electrical insulation is one of the most important components in a high voltage apparatus. Most oil-filled transformers use insulating and cooling fluids derived from petroleum crude oil, however these mineral oils have disadvantages in regards to environmental pollution and can explode, causing fires. Vegetable insulating oils have a high flash point and are more environmentally friendly when compared to conventional mineral oils. The accelerated aging processes used for these experiments were performed using two methods. First, sealed accelerated aging vessels containing insulating paper (Kraft and Diamond-Pattern) and insulating oils (both mineral and vegetable oil) were aged at 140°C for 500, 1000, 1500, and 2000 hours. The second method case used real transformer vegetable and mineral insulating oil samples which underwent accelerated aging for 42, 93, 143, 190, 240, 300 thermal cycles ranging from 30°C to 120°C. The mineral and vegetable insulating oils were tested in regards to breakdown voltage, water content, total acidity, viscosity, volume resistivity, insulating paper tensile strength, and insulating paper and oil permittivity. The breakdown voltage of the vegetable insulating oil was found to be higher than that found for the mineral oil; the accelerated aging progress decreased the breakdown voltage. The vegetable oil had a higher water saturation level than that found for the mineral oil; the vegetable oil possessed superior water characteristics (water saturation) and breakdown voltage. The viscosity of the insulating liquid is important in the impregnation process. Due to the higher viscosity of vegetable oil, special care has to be taken, especially when designing the cooling system for a large transformer.

Keywords — Insulating Testing, Life estimation, Viscosity, Breakdown Voltage, Water Content

I. INTRODUCTION

MINERAL oils used specifically for power distribution applications have been in commercial production from as early as 1899. Vegetable insulating oils extracted from seeds have been considered for use as potential transformer fluids from as early as the 1890s, however vegetable oils offered no perceived performance or economic benefits over mineral oils. Conventional mineral oils began to be scrutinized in the 1970s due to their PCB generation and also for their other undesirable health hazards and environmental impacts.

Since its introduction in the late 1990s, the use of vegetable oil as a transformer dielectric has been become common in the power industry [1]. Vegetable insulating oils have an advantage in their improved fire safety, owing to a higher flash point, and are 95–100% biodegradable, non-toxic environmentally friendly, and possess a high permittivity when compared to mineral insulating oils. Unfortunately, vegetable insulating oils also have a high pour point and viscosity [2][3].

In this paper, we discuss the basic chemical-electrical properties of vegetable and conventional mineral insulating oils. The accelerated aging of the insulating oils was performed in using two methods. The first method used a beaker containing insulating material from an oil-filled transformer for accelerated aging subjected to a constant temperature of 140°C in an oven. The second type of accelerated aging was carried out in a real 10kVA oil-filled transformer. The oil temperature was cycled from 30°C to 120°C. In each experiment, dependant on the accelerated aging time (oven experiment) or the cycles (real transformer experiment) the changes in the collected sample characteristic were analyzed. The degradation of the insulating oil after aging was determined through the breakdown voltage, the water content, the total acidity, the viscosity, and volume resistivity. Based on the results, we evaluated the relationship between the thermal stress and the long-term stability due to accelerated aging.

II. THE MATERIALS AND METHODS

A. The Insulating Oils

The insulating oils tested in this experiment were Biotran-35 (provided by the Korea D Corp.) and commercial mineral oil. The physical and electrical properties of the Biotran-35 and the mineral oil are shown in Table 1. The vegetable insulating oil has a high ignition and flash point, a high permittivity compared to the mineral oil. These advantages are useful in the electrical insulation of a oil/pressboard composite insulating system, allowing for a size reduction in the design of oil-filled transformers. However, the vegetable insulating oil has a high viscosity and pour point. The viscosity of the vegetable insulating oil is about three times higher than that found for in mineral oil. The mineral and vegetable insulating oils play many different roles. Typically, the transformer is inside the insulation and uses the oil for cooling. Therefore, the thermal conductivity
and cooling effect of the insulating oil were analyzed. In order to determine the thermal conductivity of the insulation on needs to know the specific heat and Specific Gravity. The specific Gravity of the oils is shown in Table 1; the specific heat was measured using DSC equipment. The mineral and vegetable insulating oils during transformer idle and operation in order to determine the thermal conductivity were measured using an LFA (Laser Flash Apparatus) at room temperature and 70℃. The heat capacity and thermal conductivity according to the temperature are shown in Table 3. At room temperature (25℃), the vegetable oil has higher thermal conductivity than the mineral oil. However, when the temperature was increased to 70℃ the mineral oil diffusivity and heat capacity increased. Therefore it is evident that the mineral oil has a higher conductivity compared to vegetable oil at 70℃. As shown in Table 3, as the difference between the thermal conductivity lessens, the heat dissipation effect decrease. So what is transferred to an external heat sink, depending on velocity of flow affects the heat output (this problem is due to the viscosity difference). Therefore, the use of a conventional mineral transformer-like structure for vegetable oil can lead to problems. These viscosity characteristics hamper the circulation of the generated heat found in a transformer and so have a negative influence on the heat radiation. In the use of vegetable oil, a hottest-spot analysis is essential. In addition, based on the analysis an expanded fan installation or a change in the flow velocity is recommended.

### Table I

<table>
<thead>
<tr>
<th>CHARACTERISTICS</th>
<th>Vegetable Oil</th>
<th>Mineral Oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscosity (40[℃], cSt)</td>
<td>35.12</td>
<td>7.800</td>
</tr>
<tr>
<td>Viscosity (100[℃], cSt)</td>
<td>8.010</td>
<td>2.240</td>
</tr>
<tr>
<td>Specific Gravity (15/4[℃])</td>
<td>0.924</td>
<td>0.855</td>
</tr>
<tr>
<td>Total Acid value (mg KOH/g)</td>
<td>0.08</td>
<td>0.01</td>
</tr>
<tr>
<td>Dielectric Strength (kV)</td>
<td>56.7</td>
<td>54.9</td>
</tr>
<tr>
<td>Water Content (ppm)</td>
<td>20.7</td>
<td>15.0</td>
</tr>
<tr>
<td>Dissipation factor (% , 60Hz, 80℃)</td>
<td>0.45</td>
<td>0.081</td>
</tr>
<tr>
<td>Volume resistivity (Ω . cm, 80℃)</td>
<td>3.0 x 1012</td>
<td>2.2 x 1014</td>
</tr>
<tr>
<td>Pour Point (℃)</td>
<td>-21</td>
<td>-50</td>
</tr>
</tbody>
</table>

### Table II

<table>
<thead>
<tr>
<th>Test</th>
<th>New As-received Fluid</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vegetable Oil ASTM D6871</td>
</tr>
<tr>
<td>Viscosity [cSt]</td>
<td>40℃ ≤ 50</td>
</tr>
<tr>
<td></td>
<td>100℃ ≤ 15</td>
</tr>
<tr>
<td>Water Content (mg/kg)</td>
<td>≤ 200</td>
</tr>
<tr>
<td>Acid number (mg KOH/g)</td>
<td>≤ 0.06</td>
</tr>
</tbody>
</table>

### Table III

<table>
<thead>
<tr>
<th>Contents</th>
<th>Temperature</th>
<th>Heat Conductivity (W/mK)</th>
<th>Diffusivity (mm²/s)</th>
<th>Heat capacity J /(g*K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mineral oil</td>
<td>25℃</td>
<td>0.214</td>
<td>0.125</td>
<td>2.003</td>
</tr>
<tr>
<td></td>
<td>70℃</td>
<td>0.262</td>
<td>0.140</td>
<td>2.187</td>
</tr>
<tr>
<td>Vegetable oil</td>
<td>25℃</td>
<td>0.245</td>
<td>0.141</td>
<td>1.877</td>
</tr>
<tr>
<td></td>
<td>70℃</td>
<td>0.256</td>
<td>0.139</td>
<td>1.997</td>
</tr>
</tbody>
</table>

### B. The Insulating Paper

Kraft and DPP (Diamond-Pattern epoxy coated) insulating papers are presently the most widely used insulating papers. Kraft insulating paper is made employing the delignification of wood pulp. The insulating paper contains about 90% cellulose and 6—7% lignin, with the balance being hemicellulose. The natural humidity of the paper is 4—5% by weight; the insulation is dried after winding to less than 0.5%. The dried paper is then impregnated with insulating oil, which increases its dielectric strength and also serves to cool the windings[4]. The Kraft insulating paper tested in this experiment had a thickness of 0.13mm; the DPP had a thickness of 0.20mm and an enhanced mechanical strength achieved by coating it with the Diamond-Pattern epoxy.

### C. The Accelerated Aging Sample

Aging of leading to the deterioration of insulation is a time function of temperature, moisture content, and oxygen content. Since modern preservation systems minimize the moisture and oxygen contribution to insulation deterioration, temperature become the most important controlling parameter of accelerated aging [5]. Accelerated aging of insulating oils uses an oven to facilitate the heat transfer in a container and a real oil-filled transformer causing the overload needed to alter the internal oil characteristic. Oil-filled transformers contain the insulating oil used for insulating and cooling, the insulating paper, an iron core, and copper. All of these materials effect the degradation of the transformer. The accelerated aging beaker samples used the specification laid out in Table 4. Commonly, accelerated aging material sample test methods use a metal container heated in a water bath or external and internal heating methods using heat rays. In this experiment, the temperature is the most significant factor. In the first experiment, low-moisture conditions and a constant temperature of 140℃ were employed for 500, 1000, 1500 and 2000 hours. The size of beaker was 2.0 liters and the contents were not stirred. In the second experiment, real oil-filled transformers containing material or vegetable oil were aged by repeated thermal cycling ranging from 30℃ to 120℃ Single phase 13.2kV/230V, 60Hz with a voltage regulation of 1.83 and a 97.84 percent efficiency (power factor = 1.0) were used for the 10kVA class real oil-filled transformers. In order to test the temperature rise at 120℃, 185% of the oil-filled transformer impedance voltage (385/2.92(V,%)) at 712V was applied to the windings. The inside oil temperature rose to 120℃.
and then automatic cooling of the device lowered the temperature. The transformer temperature rise and fall time for 1 cycle took a total at 16 hours. 300 cycles were run for the experiment. Samples were collected at cycle 42, 93, 143, 190, 240 and 300.

### TABLE IV
THE COMPOSITION OF THE SAMPLE USED IN THE ACCELERATED AGING BEAKER EXPERIMENT

<table>
<thead>
<tr>
<th>Material</th>
<th>Paper</th>
<th>Oil</th>
<th>Coil</th>
<th>Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight [g]</td>
<td>86</td>
<td>1215</td>
<td>1344</td>
<td>585</td>
</tr>
</tbody>
</table>

#### D. The Relationship Between Lifetime and Tensile Strength

The accelerated aging experiment was performed according to the IEEE Std C57.91-1995 standard [5]. It is the basis for the aging acceleration factor ($F_{AA}$) for a given load and temperature or for a varying load and temperature profile over a 24h period. The equation for the $F_{AA}$ is,

$$F_{AA} = EXP \left( \frac{15000}{\theta_{NT} + 273} \right)$$

(1)

where $\theta_{NT}$ is the hottest-spot temperature in °C

The loss of life percent equation is:

$$\% \text{ Loss of life} = \frac{F_{EQA} \times t \times 100}{\text{Normal insulation life}}$$

(2)

The aging acceleration factor ($F_{AA}$) is 40.5915 when the oven, temperature constant is 140°C. From Table 5, the transformer as given as having a 180,000 hours (20.55 years) lifetime; the aging acceleration factor applied using (1) was used to predict the approximate life of the transformer.

$$\% \text{ Loss of life} = \frac{40.5915 \times 2000 \times 100}{180,000} = 45.10\%$$

(3)

Obviously, there is an approximately 20°C difference between the hottest-spot temperature and the internal oil temperature in an oil-filled transformer insulation system. So, taking the hottest-spot transformer temperature into the calculation, the aging acceleration factor becomes 39.2414.

$$\% \text{ Loss of life} = \frac{39.2414 \times 300 \times 16 \times 100}{180,000}$$

$$= 104.6437\%$$

(4)

The tensile strength of the insulating paper on the life of the transformer is directly related. In addition, the tensile strength change can be determined through accelerated aging. In this paper, the tensile strength test of the insulating paper was performed based on KS C IEC 60554. The insulating paper was cut to 250 x 15mm, with a measurement speed of 20 ± 5 mm/seconds. In order to ensure the accuracy of the experiment the tensile strength tests were run nine times and average then averaged.

### III. RESULT AND DISCUSSION

#### A. The Breakdown Voltage

The electrical breakdown voltage is the most important property in liquid insulating oils. The breakdown voltage defines the ability of the fluid to withstand dielectric stresses. The breakdown voltage is sensitive to the quality of the insulating oil, which in turn can be influenced by the presence of different contaminants, such as moisture and water droplets, other emulsions, dirt, gases, and other conducting and non-conducting particles [6]. In order to test the breakdown voltage of the insulating oil according to KS C IEC 60156, spherical electrodes with a diameter of 12.5mm were used. The gap distance between the two electrodes was set to 2.5mm. The breakdown voltage was measured while increasing the voltage across the electrodes from zero at a rate of 2.0 kV/s until a breakdown occurred. The test was conducted on both virgin and aged insulation oil samples. The breakdown voltage results for the accelerated aging oil samples are shown in Figures 1 and 2. The insulating oil results from the beaker test are shown in Fig. 1. Fig. 2 displays the dielectric breakdown voltage of the real oil-filled transformer. The breakdown voltages of both insulation oils decreased uniformly according to the accelerated aging time. The breakdown voltage for the vegetable oil decreased by about 35% compared to the initial value. The mineral oil decreased by about 50% compared to the initial value.

![Fig. 1 The breakdown voltage of the accelerated aging sample](image1)

![Fig. 2 The breakdown voltage of the real oil-filled transformer cycle sample](image2)
B. The Water Content

The water content of the insulating paper and oils at room temperature are shown in Fig. 3. The water content in the vegetable oil rose sharply from 20 ppm after 50 heating cycles. When the heating was continued from 50 to 300 cycles, the water content showed a slight upward trend. The vegetable insulating oil can hold considerably more water than the mineral oil. The room temperature water saturation for the vegetable oil is about 1050 mg/kg, whereas the mineral oil is about 60 mg/kg [7]. Because of this difference in saturation levels, the vegetable oil can absorb more water than the mineral oil, and so has a greater paper drying effect. A high water content decreases the breakdown voltage and reduces the electrical strength. Combining Fig. 2 and Fig. 3 shows that the breakdown voltage of the insulation oil within a real transformer goes down slowly as the water content and conducting impurities increase as a result of the oxidation in the oil. It is assumed that as the accelerated degradation progressed, the water content in the insulating oil increased and the breakdown voltage decreased under electric and thermal stress. As a result, the high moisture affinity of the vegetable oil can be seen as a disadvantage. However, there are advantageous to obtain various characteristics that can be attributed to a high amount of water saturation compared to mineral oil which result in a better breakdown voltage.

![Fig. 3 The water content of the vegetable oil and mineral oil as a result of accelerated aging](image)

C. The Total Acidity Number (TAN)

The total acidity number of new insulating oil is normally very small. Under normal condition the acidity of vegetable insulating oils is higher than conventional mineral oil. This reflected in Fig. 4 at the beginning of the aging experiment where the TAN of new vegetable oil is higher than the mineral oil. [8] Fig. 4 shows the increase in the TAN with respect to the accelerated aging. TAN for the vegetable oil was initially at 0.09mg KOH/g and rose to 0.89mg KOH/g after 2000h of accelerated aging. The TAN of the vegetable oil increased more than that found for the mineral oil. The different chemical reaction in oils results in the vegetable oils having much higher TAN than mineral oil. On the other hand, due to the differences in the chemical structures of acids formed by vegetable oil and mineral oil, the acids formed in mineral oil are detrimental, while the acids produced by vegetable oil beneficial.[8] Commonly, increasing the TAN in insulating oil causes a decreased breakdown voltage. However, the breakdown voltage of vegetable oil is higher than that found in conventional mineral oil, as shown in Figs. 1 and 2. New vegetable oil contains small amounts of free-fatty acids that result in a TAN that is higher than that typically seen in mineral oil. As the vegetable oil is aged, the water reacted with the triglycerides comprising the vegetable oil via hydrolysis to produce long-chain fatty acids [9]. These long-chain fatty acids are mild and non-corrosive compared to the short chain organic acids found in mineral oil. Therefore, the total acidity numbers for mineral and vegetable insulating oils should not be applied using the same standards.

![Fig. 4 The total acidity numbers for the vegetable and mineral oils after accelerated aging](image)

D. The Viscosity

The viscosity is the decisive parameter in regards to the cooling capacity of an insulating fluid, which makes this parameter of particular importance. The viscosity is the principal parameter in the design calculation for heat transfer by either natural convection in smaller self-cooled transformers or the forced circulation used in larger transformers. In order to effectively remove heat from inside there are variety of ways. Install a cooling fan to the real oil-filled transformer or install a separated heat sink. Install the heat sink and use a pump to circulate the high viscosity of the flow can be a problem. A low viscosity value and a good heat transfer capability are needed in order to achieve a high performance. The results from the accelerated aging viscosity tests of the different insulating oils are shown Figs. 5 and 6. The vegetable oil has a much higher viscosity than the mineral oil at both 40°C and 100°C. Although the viscosity remains within the limits set for new vegetable oil (Table. 2 ASTM D 6871 50cSt at 40°C, 15 cSt at 100°C), the high viscosity of vegetable oil can be a critical issue regarding the safe operation of power and distribution transformers in cold weather countries. The high viscosity can cause difficulties in convection flows, the transfer of heat to cooling surfaces and in the circulation of oil to different areas of the transformer [10]. This is a critical issue and care has to be taken, especially when designing the cooling system of a large transformer.
Fig. 5 The viscosities during accelerated aging

Fig. 6 The viscosities during the real transformer cycles

E. The Volume Resistivity

Fig. 7 shows the variations in the volume resistivity ($\Omega \cdot \text{cm}$, 25$^\circ$C) over time for the accelerated aging and electrical stress of the vegetable and mineral insulating oils. The volume resistivity was initially $3.00 \times 10^{12}$ but dropped to $6.88 \times 10^9$ in the vegetable oil. The volume resistivity showed significant changes during cycles 0 ~ 42 and showed a slower rate of decrease thereafter.

F. The Insulating Paper Tensile Strength

The tensile strength of the insulating material is important in regards to the transformer’s ability to have an efficient and economic operation. Commonly, the expected life of a transformer is correlated with the tensile strength of the insulating paper. The tensile strength of the Kraft and Diamond-Pattern insulating paper results are shown in Figs. 8 and 10, respectively. The tensile strength of the aged Kraft paper in the mineral oil decreased 45% compared to the initial results. The tensile strength of the aged Kraft paper in vegetable oil decreased 30% compared to the initial value. The aged Diamond-Pattern paper in mineral oil decreased 50% compared to the initial value, the aged diamond-pattern paper in vegetable oil decreased 25% compared to the initial value. Water reacts with the triglycerides found in the vegetable oils via hydrolysis to produce long-chain fatty acids (Fig. 3) [11]. Figs. 3 and 4 show that the insulating paper aged in vegetable insulating oils remains drier than paper aged in mineral oils under the same experimental conditions. It is known that the hygroscopicity of vegetable oil is greater than the hygroscopicity of conventional mineral oil [12]. The acceptable limit for a drop in strength is up to 50% which suggests that insulating paper aging in such a high temperature for a long time can lead to a catastrophic system failure.

IV. CONCLUSION

Vegetable insulating oils are made using renewable resources, are readily biodegradable, non-toxic in water, and have a relatively low inflammability. This is in contrast to the conventional mineral oil-filled transformers currently in use today. Mineral and vegetable oils used in transformers were subjected to accelerated degradation tests in order to classify the changes in their characteristics. The chemical - electrical characteristics of the vegetable insulating oils were investigated in order to determine its suitability for replacing mineral oil. The study shows that vegetable oils have a higher breakdown voltage and insulating paper tensile strength of the oil and paper compared to mineral oil. This indicates the possibility for a much lower scope of oil-filled transformer failures. However, some aspects of the vegetable oil have to be considered, notably the viscosity and the pour point, when designing vegetable oil-filled transformers.

After the accelerated aging experiments, the vegetable
insulating oil generally maintained a good breakdown voltage, notably better than that found for mineral oil. However, the water content of the vegetable oil increased and the breakdown voltage decreased significantly. The total acidity number in the aged vegetable oil was higher than that found for the mineral oil. However, these acids do not seem to be harmful to cellulose insulation. The aged vegetable oil contains long-chain fatty acids. The long-chain acids found in the vegetable oil are non-corrosive compared to the short-chain organic acids found in conventional mineral oil. Therefore, the total acid number in vegetable oil does not cause a decrease in the dielectric strength. Vegetable insulating oil has a high viscosity and pour point compared to mineral oil. This may cause an increase in both the transformer temperature and the coil winding temperature. The results of the various characteristic changes in vegetable insulating oil were confirmed to be stable. However, when designing an oil-filled transformer with respect to the viscosity, the pour point problem found in vegetable oil must be taken into account in regards to the external environment.

ACKNOWLEDGMENT

This research was supported by the MSIP (Ministry of Science, ICT&Future Planning), Korea, under the ITRC(Information Technology Research Center) support program (NIPA-2013-H0301-13-1010) supervised by the NIPA(National IT Industry Promotion Agency)

REFERENCES


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