New liquid insulating materials for power transformers

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SUMMARY

The combination of a solid and a liquid insulation is the most frequently used insulating system in high voltage apparatus, where components have to be insulated and loss heat has to be dissipated. The requirements on the liquid part of the insulating system are not only the electric and dielectric performance but also the performance regarding environmental requirements and dehydration capability as well as low inflammability. The contribution presents a comparison of the performance of different liquids concerning the electric behaviour and some other characteristics for use in high voltage transformers.

KEYWORDS

High voltage, insulating liquids, transformer,

1 Introduction

Because of the wide availability and low cost, mineral-based transformer oils are probably the most widely used electrical insulating liquids in the world today - and have been for the past century [1]. Between 1930 and the mid seventies, non-flammable liquids like PCB were used for insulation purposes. During the 1970s it was determined, that PCBs can be an environmental hazard and can accumulate in the environment. Especially in case of a surrounding fire PCB can generate high levels of dioxins and furanes. Since that time researchers tried to find substitutes for PCB in transformers.

Since then transformers have been filled with different synthetic liquids such as silicone, ester, perchlorethylene etc. They have good dielectric, heat transfer and ageing properties, but because of their relatively high cost their use has been limited to special transformer applications [2]. One of the major advantages, forcing the application of ester liquids, is their improved environmental compatibility. Additionally these liquids comprise several extra advantages, which are at first their lower inflammability. Transformers can contain several tons of insulating liquid that may cause a long lasting pool fire in case of a transformer tank rupture due to winding failures. Some of the physical and electrical properties of mineral based transformer oil, Silicon and ester liquids are summarised in Table 1.
### Table 1: Properties of the investigated insulating liquids

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Mineral oil *)</th>
<th>Mineral oil with 20% ester liquid</th>
<th>Silicone fluid</th>
<th>Ester Liquid Midel 7131</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General physical properties</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density at 23°C</td>
<td>(kg/m³)</td>
<td>856</td>
<td>890</td>
<td>960</td>
<td>960</td>
</tr>
<tr>
<td>Density at 90°C</td>
<td>(kg/m³)</td>
<td>810</td>
<td>851</td>
<td>915</td>
<td>915</td>
</tr>
<tr>
<td>Pour point</td>
<td>°C</td>
<td>-40</td>
<td>-53</td>
<td>-50</td>
<td>-50</td>
</tr>
<tr>
<td>Toxicity</td>
<td></td>
<td>slightly toxic</td>
<td>slightly toxic</td>
<td>non-toxic</td>
<td>non-toxic</td>
</tr>
<tr>
<td>Ability to biodegradability</td>
<td></td>
<td>high</td>
<td>high</td>
<td>high</td>
<td>very high</td>
</tr>
<tr>
<td>Water solubility at 20°C</td>
<td>ppm</td>
<td>45</td>
<td>310</td>
<td>200</td>
<td>2700</td>
</tr>
<tr>
<td>Water solubility at 100°C</td>
<td></td>
<td>650</td>
<td>1600</td>
<td>1100</td>
<td>7200</td>
</tr>
<tr>
<td><strong>Heat transfer capability</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cinematic viscosity at 20°C</td>
<td>mm²/s</td>
<td>16</td>
<td>19.43</td>
<td>50</td>
<td>63</td>
</tr>
<tr>
<td>Cinematic viscosity at 90°C</td>
<td>mm²/s</td>
<td>2.3</td>
<td>3.45</td>
<td>16</td>
<td>7.7</td>
</tr>
<tr>
<td>Calorific capacity at 20°C</td>
<td>W/(m K)</td>
<td>0.135</td>
<td>0.125</td>
<td>0.151</td>
<td>0.165</td>
</tr>
<tr>
<td>Calorific capacity at 90°C</td>
<td>W/(m K)</td>
<td>0.125</td>
<td>0.125</td>
<td>0.155</td>
<td>0.155</td>
</tr>
<tr>
<td>Specific heat at 20 °C</td>
<td>kJ/kg.K</td>
<td>1.85</td>
<td>1.55</td>
<td>1.81</td>
<td></td>
</tr>
<tr>
<td><strong>Fire properties</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flash point</td>
<td>°C</td>
<td>150-175</td>
<td>&gt;335</td>
<td>310</td>
<td></td>
</tr>
<tr>
<td>Flame point</td>
<td>°C</td>
<td>130-135</td>
<td>&gt;300</td>
<td>257</td>
<td></td>
</tr>
<tr>
<td>Combustion heat</td>
<td>kJ/kg 10⁻³</td>
<td>46</td>
<td>32.2</td>
<td>36.8</td>
<td></td>
</tr>
<tr>
<td>Self ignition temperature</td>
<td>°C</td>
<td>330</td>
<td>405</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Electrical properties</strong> (all the data are relative to a temperature of 23°C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Breakdown strength (AC) U_{vol}</td>
<td>kV</td>
<td>&gt;60</td>
<td>&gt;55</td>
<td>&gt;50</td>
<td>&gt;55</td>
</tr>
<tr>
<td>Permittivity ε_{r} (25°C, 50 Hz)</td>
<td>2.2</td>
<td>2.35</td>
<td>2.9</td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td>Dissipation factor tan δ (90°C)</td>
<td></td>
<td>&lt;10x10⁻⁴</td>
<td>&lt;20x10⁻⁴</td>
<td>1.6x10⁻⁴</td>
<td>1x10⁻⁴</td>
</tr>
<tr>
<td>Volume resistivity</td>
<td>Ω cm</td>
<td>100x10⁻¹²</td>
<td>8x10⁻¹⁴</td>
<td>20x10⁻¹²</td>
<td></td>
</tr>
</tbody>
</table>

*) The data are mean values obtained from many manufacturers.

2 Description of the liquids

The investigations have been carried out using three different insulating liquids commonly used in high voltage transformers and a mixture of two of them recently proposed as insulating liquid for transformers [2]. A short description of them is presented hereafter.

2.1 Silicone Fluid

Silicone transformer fluid is one of a family of fluids known chemically as poly-dimethyl siloxanes. The chemical structure can be found in the literature [3]. Silicone filled transformers meet mostly environmental and fire protection requirements. Indeed, silicone fluid is environmentally inoffensive and flame retardant. It possesses good ageing and oxidation properties. Moreover, it does not endanger living organisms in case of emission. As far as its cooling and insulating properties are concerned, silicone can be compared with mineral oils. Its stability is related to the energy of the bond Si-O (374 instead of 245 kJ/mol for C-C bond). Silicone fluid is colourless, and characterised by a very low pour point compared to that of mineral oils even if its viscosity at 20°C is higher.
2.2 Mineral oil

Mineral oil so called "transformer oil" consists of a complex mixture of basic hydrocarbon liquids such as paraffin (40 to 60%), napthen (30 to 50%), aromatic (5 to 20%) and olefin (roughly 1%) components. The chemical structure is described in the literature [1, 4].

Their relatively good ageing behaviour and low viscosity make mineral oil a good insulating and cooling liquid. Its electrical and dielectric properties are strongly temperature and humidity dependent. The main advantages of this petroleum-based oil are its wide availability and low cost. However mineral oil possesses a low relative permittivity, a low flash point and is slightly toxic. Mineral oil possesses also the disadvantage of endangering the environment in case of a transformer leakage.

2.3 Ester Liquid Midel 7131

The ester liquid Midel 7131 used for these investigations consists of pentaerythritol-tetraester of different fatty acids. Ester liquids are non toxic, well digested by micro-organisms and posses low vapour pressure at operating temperatures of high voltage transformers. In fire they generate no dioxins or toxic products and possess a good biodegradability [5]. Previous work [6] has shown that ester liquids can be used for the retro filling of mineral oil filled transformers. These features, coupled with the ability of drying the solid insulation (impregnated paper), are considered as positive aspects. However, they are also prone to possible hydrolytic detachment through their high moisture saturation limit.

3 Relative Humidity

By definition, the relative humidity of a liquid is the dissolved water content of the liquid relative to the maximum capacity of moisture that it can hold at specific temperature. The relative humidity \( W_{\text{rel}}(\%) \) at a given absolute temperature \( T \) (K), is defined in terms of the absolute water content in the liquid \( W_{\text{abs}} \) (ppm) versus the saturation limit \( W_L(T) \) such as :

\[
W_{\text{rel}} = \frac{W_{\text{abs}}}{W_L(T)}
\]

(1)

The saturation limit of an insulating liquid depends on the type of insulating liquid, its chemical composition and its mean molar weight [7]. The temperature dependence of maximum water solubility of the insulating liquids is described by the following well-known exponential equation [7]:

\[
W_L = W_o \exp\left(-\frac{H}{T}\right)
\]

(2)

Where \( W_o \) (ppm) and \( H \) (K) are material constants, which have to be determined experimentally for each insulating liquid. The material constant \( W_o \) and \( H \) of the investigated insulating liquids can be determined from table 1. Figure 1 shows the water saturation limit of the investigated liquids for an absolute temperature range of 0°C to 100°C. As illustrated, the water solubility of ester is much higher than that of mineral oil, followed by the mixture of mineral oil with 20% ester liquid and silicone fluid. The difference in the behaviour of silicone and ester liquids compared to mineral oil can be explained by the difference in water absorption of these liquids. Ester or silicone liquid can take up water in chemically bounded and in dissolved form, while in mineral oil, water is only dissolved.
Some investigated parameters of the liquids

The aim of the investigations was to determine those physical, electrical, dielectric and ageing properties, which, according to the IEC standards, are used to classify transformer oils as to guarantee their quality and life. The most important properties are the electrical strength and viscosity, followed by dissipation factor (tan δ), water content and neutralisation number. The permittivity, dissipation factor, and AC electric strength of both the pure and the mixed liquids and their viscosity were examined. To simulate real working conditions as well as critical situations in transformers, the temperature has been varied between 0 and 100 °C along with variations in the water content of the fluid.

4.1 The water in insulating liquid

The water in the liquid originates from air moisture in the case of ‘open-breather transformer’ or ‘oil-conservator’ types, and as a by-product of oxidation reactions taking place in the liquid and the thermal decomposition of cellulose-based solid insulating materials.

4.2 Viscosity

The viscosity of an insulating liquid is important for heat dissipation and the impregnation process. It is a basic parameter in design calculations for heat transfer by either natural convection in smaller self-cooled transformers or forced convection with pumps in larger units. A low value of viscosity and a good specific heat capacity are needed to achieve a high heat transfer capability. However, high values of viscosity, such as that of ester liquids, have, compared to mineral oils, the advantage of quickly reaching the expected service temperature during a cold-restart of the transformer. Figure 3 shows a comparison of the kinetic viscosity of different liquids used in transformers. Silicon liquid shows lower viscosity in comparison to the other liquids at low temperatures. At temperatures higher than about 50 °C the viscosity of silicon liquids is higher compared to other liquids.
4.3 Heat Transfer

As mentioned before, one of the main tasks of the liquids in transformers beside the electric insulation is the heat transfer. The heat generated in the core, insulation and winding of a transformer should be transferred to the outside through the convection of the liquid. For the heat transfer of a liquid the viscosity and heat transfer quotient are responsible. Figures 4 shows a comparison of heat transfer of different liquids for transformers in comparison.

4.4 Determination of the breakdown voltage of different liquids

The methods for evaluating the properties of insulating liquids that guarantee their quality and life duration are standardised. The electric breakdown voltage at power frequency is the most often controlled parameter describing the liquid’s function as an insulant [9].

To determine the electric strength at various temperatures and for various water contents, the respective specimens were placed in the virtually homogeneous field of the VDE (Verband der Elektrotechnik Elektronik Informationstechnik e.V.) hemispherical set-up and subjected to a 50 Hz voltage increased at a rate of 2 kV/s up to breakdown. The time intervals between individual measurements were set at 5 min. between individual measurements, a glass stirrer was used to remove any solid decomposition products appearing between the electrodes, and to take away any gaseous decomposition products back in the liquid. Before and after each measurement series, the electrodes were purged of the decomposition products of preceding breakdowns. A modification in the test apparatus has already been proposed by Borsi [3]. The arcing energy was reduced by limiting the magnitude and duration of the short-circuit current, so that subsequent readings are no longer influenced by decomposition products.

The investigations were performed at different water content and temperatures. The temperatures was varied between 20°C and 120°C to simulate normal operating conditions as well as critical ones, while the water content of each insulating liquid has been varied with respect to their saturation limit at room temperature. More particularly, water content has been varied from 5 to 80 ppm for mineral oil, from 30 to 5000 ppm for ester liquid, from 20 to 460 ppm for silicone liquid.
ppm for silicone fluid and from 20 to 120 ppm for the mixture of mineral oil with 20% ester liquid. These conditions allowed reaching relative water content for more than 100%.

Because the saturation mixing ratio is also a function of pressure, and especially of temperature, the relative humidity is a combined index of the environment and reflects more than water content. The breakdown voltage is thus described as a function of relative water content. Figures 5 and 6 summarise the results of the AC electric strength investigations, showing clearly the limits \((U_1 \text{ and } U_2)\) suggested by IEC (International Electrotechnical Commission) or VDE (Verband der Elektrotechnik Elektronik Informationstechnik e.V.).

**Fig. 5: Breakdown voltage of Mineral oil and Ester liquid versus relative water content**

The investigations were only performed for new liquid specimens. However they can be useful for serviceable insulating liquids since experimental evidence indicates that liquids which are in serviceable condition or liquids submitted to accelerated oxidation tests show little change in their water solubility characteristics. Only when the liquid is severely aged or contaminated the saturation level increases significantly.

Polar compounds present in severely aged liquids are thought to influence the water solubility characteristics since water molecules can be captured by hydrogen bond with carboxyl groupings.

**Fig. 6: Breakdown voltage of Mineral oil and silicon liquid versus relative water content**

For mineral-based oil, the breakdown voltage \(U_B\) may be described as a function of relative water content (very small scatter) and thus all breakdown data at the different temperatures and different absolute humidity contents can be shown in mutual dependence. This does not apply to either silicone fluid or ester liquid. Contrary to mineral oil, there is a relatively wide scatter range for ester liquid and a investigations has been performed for high relative water content in case of silicone fluid in order to check if its dielectric behaviour decay with increasing relative water content (higher than 100%) since its behaviour is totally different from those of other investigated insulating liquids.

For ester and silicone liquids, the twin dependency of breakdown voltage on temperature and water content cannot be explained by the dependence on relative water content. Thus the breakdown of these two liquids is evidently not due to physical dissolving of the water. The difference in their behaviour compared to mineral oil can be explained by the difference in water absorption way and/or water solution states in these liquids and consequent change in their molecular structure, depending on the temperature. Ester or silicone liquid can take up water in chemically bounded form and in dissolved form, while in mineral oil, water is only
dissolved. Because the electric breakdown of insulating liquids is determined by electronic conduction processes, the molecular structure has a major effect on the level of the breakdown voltage.

4.5 Water uptake of different liquids

Figures 7 and 8 depict the results of the investigations concerning the moisture uptake rate of the different insulating liquids versus time. The temperature and ambient relative air humidity acted as parameters.

It can be seen that when testing the liquids as new ones, the limits suggested by VDE or IEC standards are respected up to a 30 days exposition only for relative air humidity of 20%. For higher relative humidity (higher or equal to 50%) the limit is respected only for a few days. But when testing the liquids as aged one, the limits remained respected up to a 30 days exposition at relative air humidity of 50% for mineral oil and the mixture of mineral oil with 20% ester liquid.

**Fig. 7: Water uptake of mineral oil versus exposition duration to wet air**

As it can be seen in figures 7 and 8, the higher relative air humidity, the higher moisture uptake rate of the insulating liquids. Also, the temperature has a very significant influence on the moisture uptake of each insulating liquids. For a given relative air humidity, the higher the temperature, the higher moisture absorption rate is.

**Fig. 8: Water uptake of silicone liquid versus exposition duration to wet air**

The reason is the saturation limit of the insulating liquid which is highly temperature-dependent. Out of figures 7 and 8 it can be generally observed that, during an exposition under some selective conditions (ambient relative air humidity and temperature), insulating liquids uptake moisture and saturate after a few days depending on the kind of liquid (moisture uptake velocity, saturation limit, temperature and initial water content) and on the outdoor conditions (relative humidity and temperature).

A part from mineral oil, a close relationship seems to exist between the relative moisture uptake rate of the different liquids and the exposition duration, information concerning the temperature being included in the relative liquid humidity. The reason of the large scatter in the values obtained for mineral oil could be related to the difference in the initial relative water content used for the investigations performed at 20°C and 60°C. But additional investigations are needed before drawing more general conclusions.
A mathematical approach of data suggests the existence of some kind of relationship between
relative moisture content of liquid and exposition time. Indeed, relative liquid humidity $W_{\text{rel}}$
can be described as a mathematical function of the exposition time $t$ (in days) representing
the solid-line curves, which fit the experimental data, plotted in figures 7 and 8.

5 Conclusion

The work presented dealt with some fundamental investigations concerning insulating liquids
actually used in high voltage transformers as insulating liquid.

Silicon liquid has good electric, dielectric, thermal and ageing characteristics. Furthermore it
has - in comparison to mineral oil - much lower inflammability and thus much lower fire risk.
If necessary, excess moisture can be removed from the fluid using standard techniques. The
dielectric strength at low temperatures is higher, than that of pure mineral oil. Therefore, the
lower risk of breakdown of the insulating liquid at low temperatures reduces the probability of
a transformer malfunction.

When considering the scenario of a defect in breathing system (for air-breathing type
transformers) it was found that at a very low ambient relative air humidity (20%), the AC
breakdown voltage limit suggested by IEC or VDE remains respected up to 30 days
exposition. For a relative humidity higher than 50% these limits are respected only for a few
days depending on the kind of insulating liquid (moisture uptake velocity, saturation limit,
temperature and initial water content) as well as on the outdoor conditions (relative humidity
and temperature). These investigations can provide practical information for monitoring
conservator type transformer in case of a bad running in the breathing system.

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