

# BEHAVIOUR OF NAPHTENIC TRANSFORMER OILS SUBMITTED TO THERMAL STRESS

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**Abstract:** *This work is devoted to the behaviour of naphthenic mineral oils of different degradation levels submitted to thermal stresses. In addition to the dissolved key gases analysis, the principal properties of the oil (dielectric strength, water content, relative permittivity, dissipation factor, and resistivity) are studied with accuracy in order to serve as an elementary diagnosis.*

**Key words:** *Thermal stress, Transformer Naphtenic Oil, Physico-chemical properties.*

## 1. Introduction

Power transformer failures are the principal reasons of long outages in power grids with serious repercussions on the system reliability, in addition to the significant loss of revenue. Transformer loading guides define the life of material in the insulation system as it is greatly influenced by temperature. The functional life of the transformer is also affected by mechanical and dielectric stresses that it endures.

Often combined with moisture effect [1-3], temperature plays an ominous role for transformer life and the electric strength as well in oil than in the paper with which it is associated [3,4].

The reduction of the Degree of molecular Polymerization (DP) of paper results from hydrolysis (water), oxidation and pyrolysis (heat) phenomena [5]. The two firsts processes are minimized by sealing the tank with an inert gas blanket over the oil to accommodate oil expansion or by utilizing a membrane in a conservator oil expansion tank. Heat is then the remaining accelerating agent which must be left to the control of operating personnel.

Diagnose devices and techniques based on live measurements of temperature are developed, in addition to numerous other techniques [1,2,6], in order to activate an alarm if threshold values are reached as well in the oil than in the paper. For instance, temperature measurements are continuously performed on operating transformers and combined with dissolved gas content in order to check for

rapidly developing failures [6].

Generally, the effect of the contaminant elements and the more compromising with regard to the ageing of oil (water, particles and oxygen) is sharply linked to the field of temperature to which the whole insulation is submitted.

This work is consecrated to the influence of temperature on the variations of dielectric strength, dissipation factor, resistivity, permittivity and water content in three oils of different levels of deterioration. This survey was led as a complement to the study consecrated to the influence of water content in oil [7]. In the perspective of elementary diagnosis, we will try to clear some intrinsic and extrinsic elements linked to the influence of temperature on the oil properties.

## 2. Experimental Technique

Three naphthenic transformer oils are considered in this work (fig.1). A new no treated Oil (A) serving as reference, oil (B) extracted from an operating transformer since 30 years, and oil (C) originating in a transformer just having a Buckholtz release after few years of service.

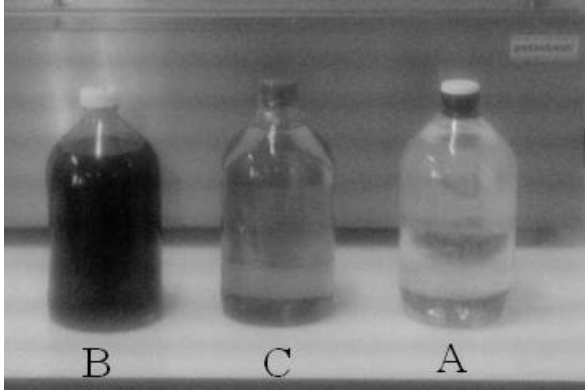


Figure 1. Check samples of the three studied oils.

Since receipt, a sample 0 is taken from each type of oil to be characterized by measurements of colour number (Col), flash point (Pe), acidity number (Ia), viscosity ( $\mu$ ) and water content (Wc0) respectively in conformity with ASTM D1500, NFT 60-103, ISO 6618, ISO 2909 and IEC 814 standards. The measurements are summarised in table 1.

Cinematic viscosity is a factor governing the heat evacuation. Ageing and oxidization of oil have tendency to increase viscosity. However, this effect is not noticeable at the considered levels of deterioration. The same interpretation is valid for the flash point. The lonely parameters that evidenced the ageing aspect of the oil are the acidity number and colour. Water content is more dependent on external factors than on the oil internal parameters. The relatively elevated values are essentially owed to the external environment of the transformers where the yearly average humidity is 80% and a mean temperature varying between 12 and 25°C.

Table 1. Some physico-chemical properties of the three oils.

Type of oil	Wc <sub>0</sub> (ppm)	$\mu$ (mm <sup>2</sup> /s)	Col	Ia	Pe (°C)
A	58.13	10.102	<0.5	0.028	140.5
B	17.73	13.501	3.8	0.1008	159
C	21.5	8.855	1	0.0224	147

For each type of oil, six samples are prepared; each one is set at a given gradient of temperature, between 20 and 120°C during a period of 1h30mn. An agitation is applied to all the samples during the heating operation under the atmospheric pressure.

For each level of temperature, the following measurements are performed: water content, breakdown voltage, resistivity ( $\rho$ ), relative permittivity  $\epsilon_r$  and dissipation factor ( $\tan\delta$ ).

The breakdown voltage is measured consistently with IEC 156 standard with a voltage rise speed of 2 kV / s. Six consecutive tests are carried out for a same filling of the test cell, with a rest of 2 mn between two tests. For each renewal of oil, the electrodes are rinsed with the removed oil.

Water content is measured directly at the opening of the bottle after having mixed the oil. An agitator was used to come closer to the most realistic results. It is important to consider the mean of 3 to 4 values corresponding to drawings in different places of the bottle.

Dissolved gases analysis in oil is performed by a gaseous phase chromatography thanks to a TFGA P200 chromatograph, consistently to the IEC 60 567. Gases are extracted by a SHAKE TEST technique.

### 3. Breakdown voltage or/and rigidity

Figure 2 depicts the different results of the variations of the breakdown voltage (KV) as a function of temperature (T °C), for the samples of the three oils A, B and C. One notices that at ambient temperature, the breakdown voltage is weak and increases with the elevation of the field of temperature. The breakdown voltage recovers values in compliance with standards from 70°C for oil A, 50°C for oil B and 30°C for oil C. That what reveals the presence of contaminant products as water, requiring among others drying of this oil before its utilization.

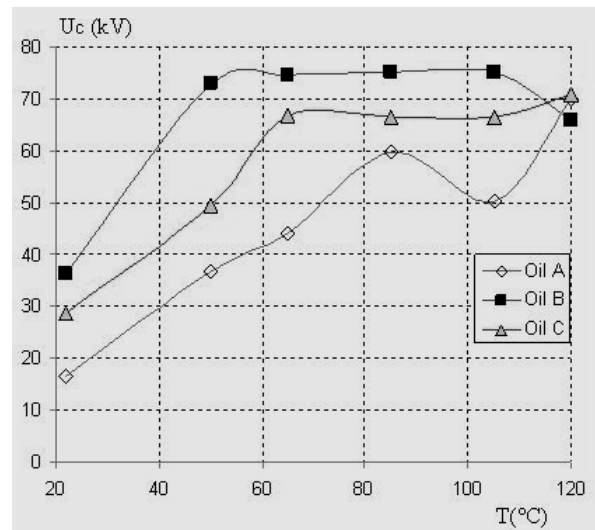


Figure 2. Breakdown voltage  $U_c$  as a function of temperature  $T$  for the three oils: A, B and C.

Breakdown voltage is greatly affected by temperature because it enables to vaporize the traces of water contained in the original oil. The increase of the dielectric strength under the effect of temperature is always accompanied by the decrease of moisture. It is valid for the three types of oil (A, B and C). This effect is however more spectacular in oil A. This improvement is attenuated when water content is reduced to 15 ppm. A temperature of about 60 °C is sufficient to lead the oil at this level of quality with regard to the strength and water content. In the same way, the application of discharges to the three samples of oil presents a trend to decrease water content at weak temperatures, notably for oil A [7]. This effect is reduced when the oil is submitted to more elevated temperatures.

#### 4. Water content as a function of temperature

Figure 3 presents the variations of water content in the three types of oil according to the applied temperature. It decreases greatly for oil A that contains substantial quantities of water at the origin. Beyond 60°C, the variation is less spectacular for the three liquids. It becomes enough delicate because it can even increase at the time of manipulations as a consequence of its interaction with the humidity present in the laboratory atmosphere, it is suspected at 105°C for oil C. In spite of the elevated levels of applied temperature, water content doesn't be null. It remains however below the limit of 10 ppm fixed by the most severe standards.

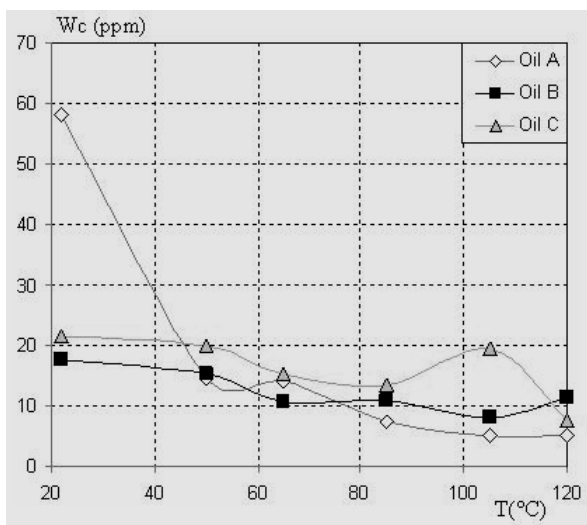


Figure 3. Variations of water content Wc (in ppm) as a function of temperature for the three oils.

#### 5. Relative permittivity $\epsilon_r$ as a function of temperature

The permittivity is a non dimensional value; it depends on the internal structure of the oil, and characterizes the polarity between molecules. Figure 4 represents the chronology of variation of the permittivity as a function of temperature for the different samples of oil.

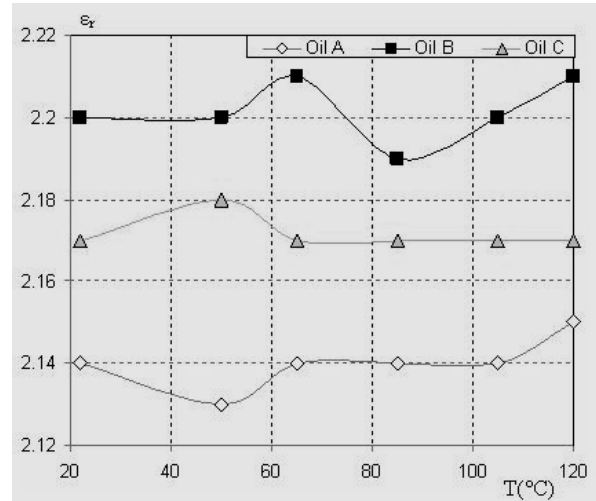


Figure 4. Variations of permittivity  $\epsilon_r$  as a function of temperature for the three oils.

The permittivity presents a more complex trend to variation when oil temperature is increased. This variation is however modest (between 2.13 and 2.15 for oil A, between 2.19 and 2.21 for oil B and between 2.16 and 2.18 for oil C). An interpretation of the condition of the oil based only on this parameter is difficult. This could be possible with the combination with the dissipation factor  $\tan \delta$ .

On the other hand, it appears clearly that the relative permittivity increases, whatever is the temperature, with the age of the oil that is in direct relation with its colour. Moreover, a relatively weak number of discharges (48 applied discharges of about 20mJ) didn't have significant effect on the general condition of the oil in order to impair its relative permittivity.

#### 6. Dissipation factor ( $\tan \delta$ ) as a function of temperature

Figure 5 represents the variations of  $\tan \delta$  as a function of temperature for the three studied oils. The dissipation factor, in the same manner of water content with which it is highly linked, is affected by temperature whatever the operating frequency regime [8].

At ambient temperature where water content is relatively elevated in oils A and C (presence of oil ageing products), the value of  $\tan \delta$  is relatively important with regard to those recorded progressively when increasing temperature, that what means that we are in presence of a non soluble aqueous phase. Then, oil conductivity increases consequently to the movement of water particles under the effect of the electric field which affects  $\tan \delta$ .

From the weakness initial value of water content in oil B, the increase of temperature didn't have a meaningful effect on dissipation factor. This can be owed to the relatively best miscibility of water in this liquid as well as to the presence of other contaminant compounds whose effect is predominant on the variations of  $\tan \delta$ .

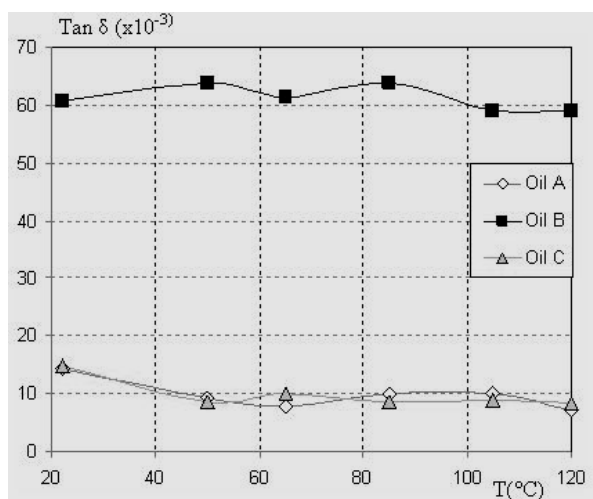


Figure 5. Dissipation factor  $\tan \delta$  as a function of temperature in the three oils.

On the other hand, the fact that oil B presents, whatever is the temperature, values of  $\tan \delta$  more elevated than those of the two other types of oil, suggests that particles that are in greater number in this oil (fig.6) play a major role with regard to the presence of water. Indeed, the oxygen bridge between glucose rings is affected by water [5], causing a rupture of the chain and the formation of two  $-OH$  groups, each attached to its monomer. The result is the reduction of PD and shortening and weakening of the fiber.

The variations of the ratio  $(n_2/n_1)$  between the number  $n_2$  of measured particles in oil B and the number  $n_1$  of particles in oil A as a function of their diameter  $D$  evidence that as the oil deteriorates, little dimension particles ( $D < 15 \mu m$ ) are generated in larger number with regard to those of great dimension ( $D > 15 \mu m$ ).

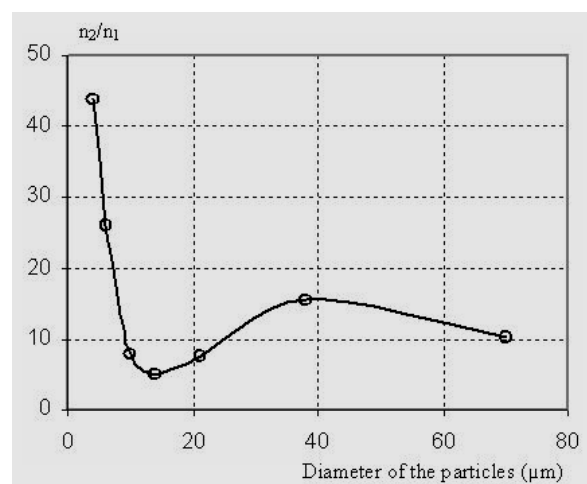


Figure 6. Variations of the ratio  $(n_2/n_1)$  between the number of particles measured in oil B and the number of particles in oil A as a function of their diameter.

## 7. Resistivity $\rho$ as a function of temperature

This parameter expresses the resistive nature of the oil. It depends on the molecular aspect and the existing particles within the oil in the electric meaning, and under the effect of polarity in the physical meaning.

In figure 7 are presented the variations of the resistivity  $\rho$  as a function of temperature.

Results obtained for oils A and C show that the resistivity increases with the growth of temperature until  $T=65^\circ C$  after which it evolves by oscillating until reaching the maximal value at  $T=120^\circ C$ , meaning that the conductivity decreases while temperature is increased. This effect tends to minimize the charge displacement and confirms the good quality of oil insulation. Some measurements bring up a tendency to the decrease of resistivity, as it is the case for oil A at  $105^\circ C$ ; it can be owed to the effect of humidity which is present in the laboratory.

In oil B, the resistivity varies in an oscillating manner around an average value nearly constant of  $3.72 G\Omega m$ . It presents a weak sensitivity to variations of temperature. Its age, relatively elevated with regard to oils A and C, acts so that, in spite of its weak water content, its resistance remains weak; suggesting then that the condition of this oil is more dependent on other contaminants.

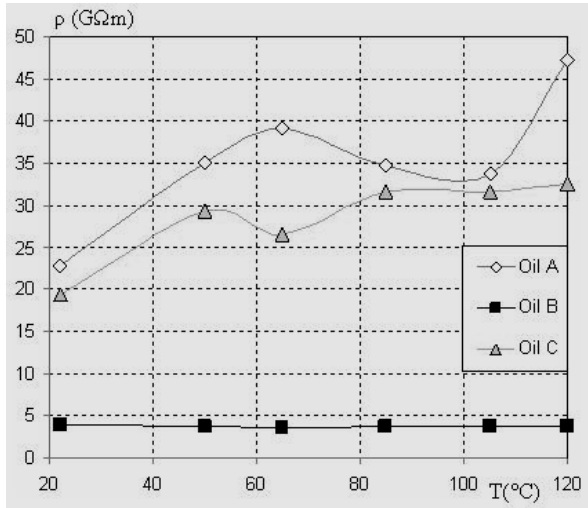


Figure 7. The average resistivity  $\rho$  as a function of temperature for the three oils: A, B and C.

Contrarily to the permittivity that is exclusively a constitutive characteristic of the oil (intrinsic), the resistivity is one of the parameters that are greatly dependent on the conditioning of this oil.

For instance, oil resistivity is influenced by the presence of impurities (dusts, particles, gas and humidity) that, even in so weak quantity than few ppm, have a significant effect on the measured values [9]. On the other hand, more the temperature is raised, more the viscosity of the liquid is weak and more higher is the mobility of ions, and therefore more the conductivity is increased. Since dissociation of the impurities in ions is the more elevated than temperature is higher, the liquid resistivity would have then tendency to decrease when temperature is increased. This effect is reinforced in the case of oil B which contains more impurities than the two other liquids, where this effect compensates the limitation of water content. This is not the case for oils A and C where the effect of the limitation of water content is dominating.

In spite of the best intrinsic parameters presented by oil C ( $\epsilon_r$ ,  $\tan \delta$  and  $\rho$ ), this latter remains unusable with regard to oil B that presents only a better dielectric rigidity and a slightly weaker quantity of moisture. These parameters prove out to be incapable to provide lonely a formal diagnosis on the oil condition.

## 8. Dissolved gases report of oil C

Despite the fact that the transformer from which is extracted oil C is submitted to a Buckholtz release, the only parameters that are below standard recommendations are: breakdown voltage

$U_d = 28.57 \text{ kV} < 50 \text{ kV}$  and water content that overtakes slightly the maximal recommended value ( $21.52 > 20 \text{ ppm}$ ). For this purpose, we resort to the historic of the dissolved gas analysis in this oil. In table 2 are summarised the results of the dissolved gas recorded during the last eight years, where the quantities of gas are expressed in ppm. Figure 8 represents the characteristic gas variations of the detected gases where  $\text{CO}_2$  quantities are very superior to those of the other gases. This latter, as well as Carbon monoxide  $\text{CO}$ , is however known to not be a default gas [10] and indicates clearly that the origin of the failure is located in the solid insulation.

The preliminary diagnosis that one can give out is that the variations of the relative volumes of acetylene and hydrogen are abnormal; the transformer seems to be the seat of an electric arc that could depend much more on the condition of the solid insulation or/and the connecting points as well as a possible overvoltage that can be at the origin of electric arcs.

Detected gas	Date			
	11/2001	05/2004	07/2007	03/2008
$\text{H}_2$	5.0 ppm	<1.0	17.0	493.0
$\text{CO}$	233.0	89.0	84.0	341.0
$\text{CH}_4$	18.0	<1.0	6.0	121.0
$\text{CO}_2$	4176.0	1975.0	1724.0	1767.0
$\text{C}_2\text{H}_4$	48.0	33.0	61.0	204.0
$\text{C}_2\text{H}_6$	46.0	17.0	23.0	29.0
$\text{C}_2\text{H}_2$	11.0	14.0	17.0	326.0
Oil Temp(°C)		42.0	54.0	30.0

Table 2. Historic of the dissolved gases detected in oil C.

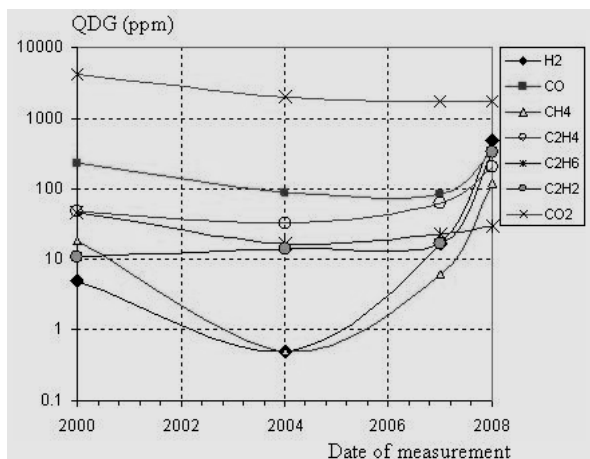


Figure 8: Chronological evolution of the quantities of dissolved gases (QDG) (logarithmic scale) as a function of the date of measurement.

## 9. Conclusion

Thermal and electric ageing origins are less linked, only the strength seems to be affected by electric defaults of oil C. The other parameters (resistivity,  $\tan\delta$ ,  $\epsilon_r$  and water content) remain less sensible to this type of default. The generation of high quantities of default gases affects very weakly these parameters.

The physico-chemical analysis combined with the dissolved gases analysis enable not only to evaluate the general condition of the oil, but also to enlighten the reasons of insulation deterioration or the origin of contaminating factors, and then to make efficiently the appropriate measures in order to ensure the safety working of the equipment.

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