GASSING OF THE ELECTRICAL INSULATING FLUIDS - A DETERMINANT FACTOR OF THE TRANSFORMERS SAFETY IN OPERATION

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Abstract - The influence on the quality of the electrical insulating fluids on the safety in operation of the transformers has been evaluated. After processing the comparative experimental data obtained by gas chromatography technique on 5 different sorts of electrical insulating fluids (a sort of vegetable oil with high oleic content and with addition of 0.5% antioxidant "functional model" - compared with two commercial sorts of mineral oil, 1 mainly vegetable commercial oil, 1 commercial synthetic ester), thermal aged in contact with electrical insulating paper and copper for electrical use, at 110 ± 3 °C for 1000 hours in closed vessels (limited access to atmospheric oxygen) it has been found that at the transformers filled with mineral oils, the risk of explosion and fire is approx. 10 times higher than those filled with synthetic or vegetal ester. It has also been found that the ageing of the insulation paper is approx. 15 times slower in the synthetic and natural ester than in the mineral oils normally used in transformers.

Keywords: transformer oils, mineral oils, synthetic esters, natural esters, explosion risk, fire risk, insulating paper ageing

1. INTRODUCTION

The issue of sustainability and safety in operation of electrical equipment, including those which use electrical insulating fluids (oils), is of a great theoretical complexity and practical importance.

The durability and safety in operation of the electrical installations under voltage is determined, firstly by the ageing of the insulation systems, which during operation are exposed simultaneously to electric, thermal, chemical, mechanical stress (vibrations), etc. [1, 2]. In the case of power transformers in order to ensure both adequate insulation and heat transfer to the environment, electrical insulating fluids (transformer oils) with or without the addition of magnetic nanoparticles are used [3-6]. During operation, the electrical insulating fluids used in transformers, interact with atmospheric oxygen thermal-oxidative degradation processes [7 - 11]) and with the materials they are in contact (copper, paper and / or cotton insulations etc.) on which may corrode / degrade [2, 11 - 20]. The corrosive aggressiveness of mineral insulating oils is primarily due to their sulfur content [13, 16-20]. Copper corrosion products, whether they dissolve in oil or form powdered products (sulphides nanoparticles) which disperse in oil and / or deposit on the paper insulations, drastically reduce the dielectric rigidity of the insulation system [16-21], which can lead to transformer failure [22]. It has been revealed that the interactions between the electrical insulating fluid and cellulose from the transformer's insulation (paper) forms a series of furan products which dissolve in oil and by complex chemical reactions lead to water and gas formation - primarily CO and CO_2. By monitoring of the furans, CO and CO_2 content, the residual lifetime of the transformer [15, 23 - 28] can be assessed. All these corrosion and / or degradation processes are accelerating under the action of thermal stress.

On the other hand, under the influence of thermal stress, the insulating oils suffer a series of decomposition processes, i.e. breaking of carbon-carbon bonds and formation of flammable / explosive gases such as H_2, CH_4, C_2H_4, C_2H_6 etc. [29, 30]. In extreme situations (accidental overloading and inappropriate maintenance / exploitation) the excessive gas formation can lead to the explosion of the transformer and to burning of hot oil (Figure 1) [31] - **with all related economic, social and environmental consequences** [54].

Fig. 1. Explosion and simultaneous incineration of several transformers in Botosani (RO) [31]

Traditionally, mineral oils are used in transformers, which, although having adequate electrical characteristics and a relatively low cost, have a number of disadvantages, such as a relatively low flammability point (maximum 135°C), due to the sulfur content are corroding the metallic parts, degrading the insulation paper with gases, water and furans (toxic products) forming, are hard biodegradable [32-34]. Considering these, numerous studies and researches [7-9, 12-15, 28-30, 35-37] are concerned with the alternative use of electrical insulating fluids based on synthetic esters (relatively expensive) and especially those based on vegetal esters - which are relatively inexpensive, are obtained from renewable resources, are easily biodegradable, have a flammability point above 270°C (hardly inflamed), etc.

It is noteworthy that due to technological developments and the expansion of reactive consumers that increase the harmonics share [38-43] (such as computers, LEDs, etc.), the effect of electrical stress that leads to degradations of insulation systems, including those complex - oil / paper is more pronounced.

Considering these, the *aim of the work* is the experimental determination of gases releases due to thermal stress in various electrical insulating fluids in contact with electro-insulating paper and copper for electrical use.

2. EXPERIMENTAL – PROCEDURES

For quantitative and qualitative determination of the gases formed under the influence of thermal stress during the ageing of electrical insulating oils in simultaneous contact with the copper for electrical use and with electrical insulating paper on the gas formation, 150 grams of oil sample were introduced into Erlenmeyer's flasks with ground slide and ground stopper.

For each kind of investigated oil (Table 1) there was a sample of pure oil (blank) and a sample in which were submerged approx. 100cm^2 copper foil for electrical use (thickness 36 ± 4µm) [44] and approx. 100cm^2 Kraft insulation paper (22HCC type manufactured by Weidmann).

Table 1. The investigated electrical insulating oils

Sample code	Composition	Type / manufacturer
Oil 1	Mineral oil	MOL TO-30.01R [45]
Oil 2	Predominantly vegetal ester	Biotemp® [46]
Oil 3	Synthetic ester	LUMINOL [47]
Oil 4	Vegetal ester with 0,5% antioxidant	MF-UPMEE; P1MF [48]
Oil 5	Mineral oil	Nynas [59]

The sample flasks thus prepared were closed with a plug (access restricted to atmospheric oxygen) and exposed to thermal storage at 110 ± 30°C for 1000 hours in a France Etuve type XL 980 oven.

Prior to thermal treatment and periodically, the gases contents of the investigated oils were determined with a Perkin Elmer 600 CLARUS (USA) gas chromatograph.

3. RESULTS

The results of gas chromatography and the evolution of total volume of gases ($H_2 + CH_4 + C_2H_4 + C_2H_6 + CO + CO_2$ - formed (expressed in liters under normal conditions relative to the oil mass [nL/kg]) during the thermal treatment applied to the investigated oils are shown synthetically in Fig. 1 (in the oils without contact with electrical insulating paper and / or copper) and in Fig. 2 (in the oils in contact with paper and copper).

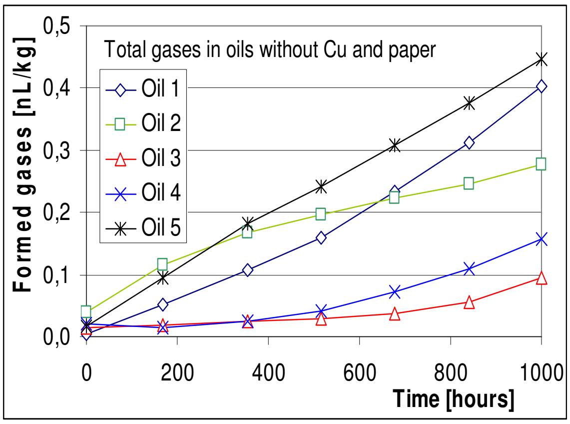

Fig. 2. The evolution of total gas forming in the investigated oils (simple - without Cu and paper)

The analysis of Fig. 2 has been revealed that during thermal treatment applied to the investigated oils - without being in contact with electrical insulating paper and / or copper – take place degradation processes with gases forming - carbon oxides (CO and CO_2) and easily flammable / explosive gases (H_2, CH_4, C_2H_4 and C_2H_6).

The mechanisms of flammable / explosive gas forming have been described in [29], and the forming of CO and CO_2 is the result of oxidation processes of organic compounds with dissolved oxygen in oil (processes that are time-limited by consumption of the dissolved oxygen in oil [30, 50]). It is also noted that gases forming processes are much more intense in the investigated mineral oils (Oil 1 and Oil 5) than in the synthetic ester (Oil 3 - about 4.5 times) and vegetable ester (Oil 4 - approx. 3 times).

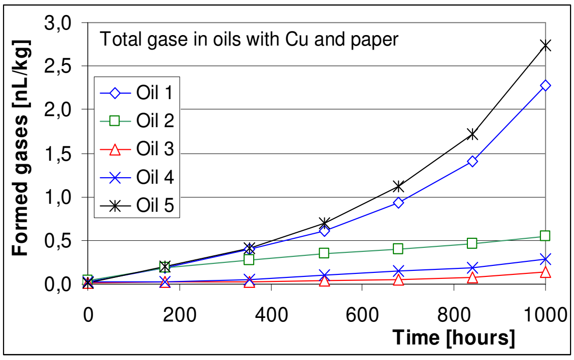

Fig. 3. The evolution of total gases forming in investigated oils in contact with paper and Cu

By comparative analysis of Fig. 2 and Fig. 3 it observed that during the thermal treatment of the investigated oils in contact with electrical insulating paper and with the copper for electrical use, the degradation processes with gases forming are substantially increased - after 1000 hours the gases forming increases from 0.4 to 2.3 nL / kg at O1 (about 6 times), from 0.28 to 0.55 nL / kg at Oil 2 (about 2 times), from 0.1 to 0.2 nL / kg at O3 (about 2 times), from 0.16 to 0.25 NL / kg to O4 (about 1.5 times), respectively from 0.45 to 2.8 nL / kg at O5 (about 6.3 times). These increasing is partly due to the catalytic effect of the copper on the flammable / explosive gases forming processes [29], and on the other hand to the forming of furan products with CO and CO_2 forming because of degradation of cellulose from the electrical insulating paper [30].

From the analysis of Fig. 3 has been found that under practical conditions of operation (electrical insulating fluid in contact with electrical insulating paper and copper - system exposed to thermal and electric stress), the gases forming in the investigated mineral oils is significant. The gases forming leads to a substantial increase of the pressure from the transformer tank which, in the absence of a properly designed and maintained (functional) safety system (pressure transducer coupled with a power voltage decoupling system and exhaust valve) can lead to the mechanical failure (explosion) of the tank followed by ignition of flammable gases and hot oil (Fig.1).

It is noted that the total volume of the formed gases (Fig.3) is a determinant stress factor of the mechanical integrity of the transformer tank and the ratio of the easily flammable gases, respectively the ratio $k1 = (H_2 + CH_4 + C_2H_4 + C_2H_6)/(CO+CO_2)$ indicates the risk of ignition (ignition temperature) of formed gases and the oil (usually hot). The Fig. 4 and Fig. 5 shows the *k1* evolutions during the thermal treatment applied to the investigated oils without contact, respectively with electrical insulating paper and copper.

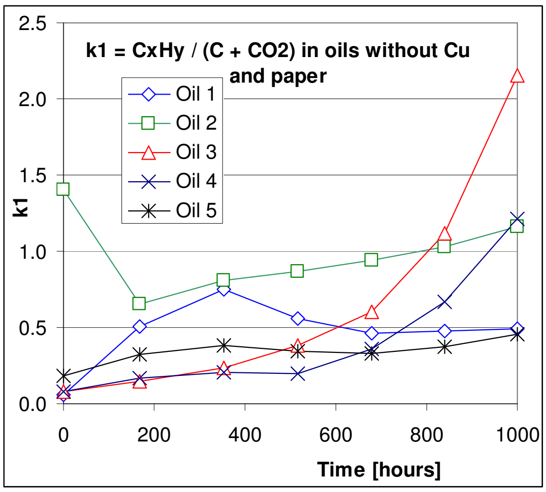

Fig. 4. Evolution of the CxHy / (CO + CO_2) ratio in investigated oils (plain - without Cu and Paper)

From the analysis of Fig. 3 and Fig. 4 it is found that in synthetic oil Oil 3 and natural ester Oil 4, after consumption of oxygen dissolved in oil with the CO and CO_2 formation, the H_2, CH_4, C_2H_4 and C_2H_6 formation processes are dominant. The oxygen content dissolved in mineral oils is 2-3 times higher than in ester oils [50] and as a consequence, in O1 and O5 dominates the CO and CO_2 formation.

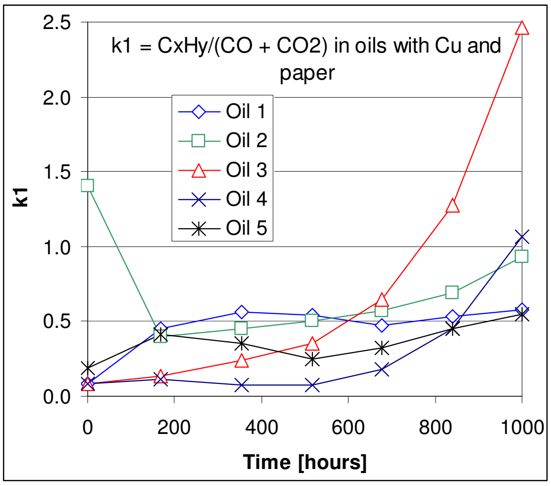

Fig. 5. Evolution of the CxHy/(CO + CO_2) ratio in the investigated oils in contact with paper and Cu

From the data presented in Fig. 3 and Fig. 5, the fire risk of the transformer can be assessed by calculating the content in flammable gases, respectively (1):

$$\text{Flammable gases [nL/kg oil]} = k1 \cdot V_T / (k1 + 1) \qquad (1)$$

where V_T is the total volume of the formed gases (Fig. 3).

Fig. 6 presents the evolution of the total volume of flammable gases formed during the applied thermal treatment.

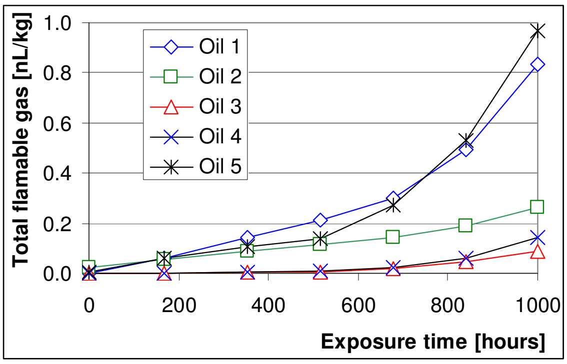

Fig. 6. Evolution of flammable gases formed by the thermal ageing of the investigated oils

The analysis of Fig. 6 has been revealed, that the volume of flammable gases formed after 1000 hours of thermal treatment at 110 ± 3°C in mineral oils Oil 1 and Oil 5, is approx. 10 times higher than in Synthetic Oil 3 and vegetable ester Oil 4, which leads to the conclusion that transformers filled with mineral oil have a fire risk of approx. 10 times higher than those filled with electrical insulating fluid based on esters.

In operation, the insulation of the transformers is exposed simultaneously to the thermal and electric stress. Under the action of thermal stress, the paper insulation in contact with oil suffers a series of degradation processes with the formation of furan products, CO_2 and CO [15, 30] - the content in these oil products being a good indication for assessing the ageing degree of the paper insulation. Under these conditions, the CO_2 and CO content generated during operation due to paper insulation degradation (as a difference between CO_2 and CO formed in the oils investigated with or without contact with electrical insulating paper) is a good indication on the compatibility of the oil with electrical insulating paper and implicitly of the risk of the transformer failure through the insulation penetration. Fig. 7 presents the evolution of the CO_2 and CO content formed due to the degradation of the electrical insulating paper relative to the total gases content formed in the investigated oils (2):

$$k_2 = (V_1 - V_2)/V_T \qquad (2)$$

where V_1 is the volume of CO_2 and CO formed in the investigated oils in contact with paper and Cu and V_2 in oils without Cu and paper. In Fig. 8 is presented the evolution of CO + CO_2 formation due to the degradation processes of the electrical insulating paper.

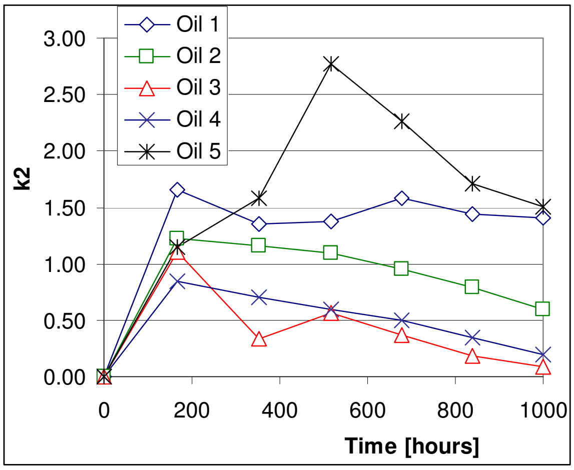

Fig. 7. Evolution of the weight in the CO + CO_2 formed gases resulted from the degradation of the electrical insulating paper

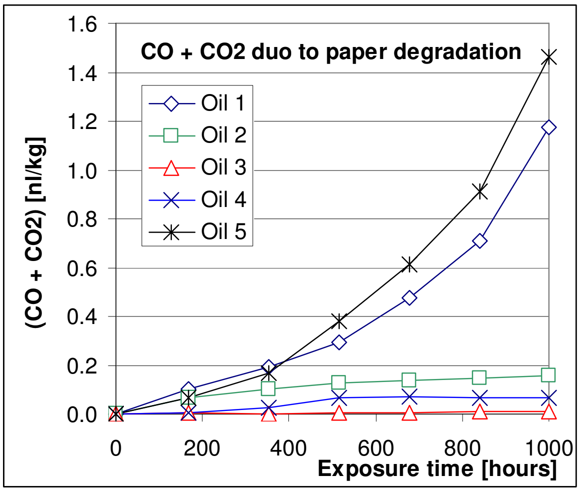

Fig. 8. CO and CO_2 formation due to paper degradation

By analysis of Fig. 7 and Fig. 8 has been revealed that the formation of CO and CO_2 due to the degradation processes of electrical insulating paper is more than 15 times faster in mineral oils Oil 1 and Oil 5 than in the synthetic ester Oil 3 and vegetable ester Oil 4. This finding leads to the conclusion that the durability of mixed oil paper insulations is approx. 15 times lower for mineral oils than for ester oils.

From the data presented in Fig. 3, Fig. 6 and Fig. 8 has been found that the safety and duration in operation of the esters-based electrical insulating fluid transformers is approx. 15 times higher than those with traditional mineral oil. In view of this consideration, as well as the fact that natural esters (vegetable oils) obtained from renewable resources by environment-friendly technologies are non-toxic and biodegrade quickly under natural conditions, do not corrode copper, etc., in the view of sustainable development and environmental protection it is advisable to replace the traditional mineral oils with natural esters (vegetable oils) in electrical applications. In this context, it is considered necessary that, through sustained environmental information [51-53], manufacturers and users of electrical equipment to be convinced to renounce at using of traditional mineral oils in the favor of vegetable oils.

4. CONCLUSIONS

After processing the comparative experimental data obtained by gas chromatography technique on 5 different sorts of electrical insulating fluids (a sort of vegetable oil with high oleic content and with addition of 0.5% antioxidant "functional model" - compared with two commercial sorts of mineral oil, 1 mainly vegetable commercial oil, 1 commercial synthetic ester), thermal aged in contact with electrical insulating paper and copper for electrical use, at 110 ± 3 °C for 1000 hours in closed vessels (limited access to atmospheric oxygen) it has been found that:

- the total content of gases formed in the investigated mineral oils is approx. 10 times higher than in esters-based electrical insulating fluids;
- the total amount of flammable / explosive gases formed in the investigated mineral oils is approx. 10 times higher than in esters-based electrical insulating fluids;
- the total amount of CO and CO2 formed due to the degradation of the insulation paper in the investigated mineral oils is approx. 15 times higher than in esters-based electrical insulating fluids.

Based on these experimental findings, the main conclusions are:

➢ The risk of explosion and devastating fires in transformers filled with traditional electrical insulating fluids (mineral oils) is approx. 10 times higher than in those with esters-based electrical insulating fluids;

➢ The ageing of the paper insulation is approx. 15 times faster at mineral oil transformers than at those based on esters;

➢ The electrical insulated fluid Oil 4 "functional model" oil has a behavior in operation close with that of synthetic oil Oil 3, so it is a relatively cheap alternative (near costs, even lower than at mineral oils) and environmentally friendly for use in transformers with high safety and durability in operation.

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