

Power Distribution Transformers using Natural Ester Fluids as Dielectric and Coolant

Transformadores de Distribución que operan con Aceite de Origen Vegetal como Dielectrico y Refrigerante

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Abstract– Researches related with the use of Natural Ester Fluids as refrigerant of power transformers has been developed in other countries with successful results. In Colombia there is no a procedure to control the use of these esters in electrical apparatus, so the current implementations are regulated by NTC 1465 standards for mineral esters. This new proposal involves the composition and the most relevant properties (the ignition resistance, impact on the lifetime of the insulating papers and the impact on the environment), which makes the application of natural esters fluids advantageous not only to preserve the environment but also to get a better performance of power transformers.

Keywords– Natural Ester Fluid, distribution transformers, electrical apparatus, environment, chemical properties.

Resumen– Las investigaciones en desarrollo respecto al uso de aceites de origen vegetal como refrigerantes en transformadores de distribución han tenido resultados destacados en otros países. En Colombia no existe un procedimiento para monitorear la aplicación de estos aceites en equipos eléctricos, por lo tanto la actual implementación se regula por la norma técnica NTC 1465 para aceites de origen mineral. Esta propuesta de nueva tecnología contempla la composición y las propiedades más relevantes (resistencia a la ignición, impacto en el tiempo de vida del papel e impacto en el medio ambiente), lo cual provee de mayor número de ventajas al aceite vegetal y un mejor desempeño en eficiencia.

Palabras clave– Aceite de origen vegetal, transformadores de distribución, equipos eléctricos, medio ambiente, propiedades químicas.



I. INTRODUCTION

Power transformers started to use natural ester fluids as is the case of a Panama Utility where a pad-Mounted transformer operates with ester fluids as coolant. Patents and regulations have been presented in order to guarantee their production, commercialization and final use. The American Section of the International Associations for Testing Materials (ASTM) has regulated their technical specification.

The Colombian Technical Normative (NTC) adopted requirements for these natural esters fluids based on ASTM. This survey cover two perspectives: the regulatory specifications for natural ester fluids used in electrical apparatus as transformers taking into account their electrical, physics and chemical characteristic. For another hand the survey refers to important issues on natural ester fluids. Also, this paper consolidates results of a survey developed by utilities in Caribbean Coast of Colombia.

II. REGULATORY SPECIFICATION FOR NATURAL ESTER FLUIDS USED IN ELECTRICAL APPARATUS

In Colombia, the technical standard NTC 1465 establishes requirements for mineral ester fluids used in equipment such as transformers, switches and electrical apparatus [1].

However, the NTC 1465 only establishes the requirements to be accomplished by electric systems and apparatus that use mineral ester fluids according with the technological availability in Colombia. Otherwise, NTC 1465 was focused in the reduction of Polychlorinated Biphenyls (PCB) that used to be inside of Mineral Ester Fluids. Therefore, the continuous process of investigation and the continuous research in reduce the dependence of fluids derived from mineral oil has brought the implementation of new materials in which is included the use of natural ester fluids as dielectrics [1], [2].

During the investigation process, a contrast of the available limits of operation established in NTC 1465 was done according with the established in

TABLE 1. REQUIREMENT COMPARISON THAT ARE PROPOSED IN ASTM D6871 (SPECIFICATION FOR NATURAL ESTER) AND THE NTC 1465 (SPECIFICATION FOR MINERAL OIL IN COLOMBIA DERIVED FROM ASTM D3487) [1], [6], [30], [21], [22]

No	Type	Characteristics	Limit values	ASTM reference normative used for Natural Ester Oil	Limit values	ASTM reference normative used for Mineral Oil
1	Physicals	Maximum Color	1,0	D1500	0,5	D1500
2		Visual examination	Bright and Clear	D1524	Bright and Clear	D1524
3		Maximum Fire Point (°C)	300	D92	145	D92
4		Maximum Flash Point (°C)	275	D92	63 - 80	D611
5		Maximum Pour Point (°C)	-10	D97	-30	D97
6		Relative density	0,96	D1298	0,865 - 0,91	D1298
7		Maximum Viscosity 100°C/40°C	15/50	D 445 / 88	"3 /12	D 445
8	Chemical	Corrosive Sulfur	No corrosive	D1275	Not corrosive	D1275
9		neutralization Number	0,06	D974	0,025	D974
10		PCB content (PPM)	No detectable	D4059	50	D4059
11		Maximum water content	200	D1533	30	D1533
12	Electrical	Maximum Gassing tendency	0	D2300	15	D2300
13		Dissipation factor @ 60 Hz 25°C / 100°C	0,2/4,0	D924	0,05/0,3	D924
14		Dielectric Breakdown before treatment	30	D877	30	D877
15		Dielectric Breakdown After treatment 1 mm (0.04 in.) gap / 2 mm (0.08 in.) gap	20/35	D1816	28/56	D1816
16		Dielectric Breakdown voltage under impulse conditions (25°C, min, kV)	130	D3300	145	D3300

ASTM D6871. There were presented parameters for natural ester fluids operation, this comparison was done with sixteen properties in which were involved physical, chemical and electrical specifications that must be verified in both ester fluids types [3], [4], [5].

Table 1 resume the available specification for each type on fluids.

As is shown in table 1, the high performance of natural ester oils allows a higher fire point in contrast with mineral oils. The following considerations are relevant and advantageous for its implementation [2]:

- a. Their Operation Compatibility with typical materials used in construction and assembly of electrical equipment.
- b. Their natural origin from agricultural product which makes them less flammable.
- c. They are free of Polychlorinated Biphenyls (PCB) due to its natural origin.
- d. Their Greater fire point which make it resistant to adverse operative conditions during transient events.

ASTM 6871-03 suggests especial consideration considering the following properties: physical conditions (aniline point, interfacial tension pour point), chemical (water content, neutralization number, oxidation inhibitor content, oxidation stability) and electrical (dissipation factor). ASTM 6871-03 also establishes typical values to considerate during the filling process in which must be verified the proprieties of the natural ester fluids to validate its operation. Table 2 define the range value considered as typical and normative reference that allows testing processes [6].

TABLE 2. COMMON PROPERTIES FOR VEGETABLE DIELECTRIC

Proprieties	Typical Values	ASTM
Expansion Coefficient (°C ⁻¹)	0,0007 a 0,0008	D1903
Dielectric Constant @ 25 °C	3,1 a 3,3	D924
Specific Heat	0,45 a 0,6	D2766
Thermal conductivity	0,0035 a 0,0045	D2717

Previous works related with transformers that operate with natural ester fluids suggest the revision of some properties in order to be in rule with the standards specification presented in table 3. These parameters are monitored during the survey allowing the identification of their performance in stable operation of the system as is the case of the temperature of the oil.

However water existence inside of the transformer as is established in ASTM D6871 allows that the natural ester fluids do not generate the proliferation of microorganisms inside of the transformer tank due to the presence of degraded oil considering a

very dry environment for this species if it is kept lower than 300 ppm.

TABLE 3. STANDARD REFERENCES FOR THE MONITORING OF TRANSFORMERS THAT OPERATES WITH NATURAL ESTER FLUIDS

Test	During the energizing process	During Normal operation
Breakdown Voltage (kV)	IEC 60156	IEC 60156
Moisture (ppm)	ASTM D1533	IEC 60814
Acidity (mg of KOH/g of oil)	ASTM D974	AS 1767.1
Interfacial Tension (mN/m)	ASTM D971	ASTM D971
Dielectric Dissipation Factor	IEC 60247	IEC 60247

III.DISCUSSION: FUNDAMENTAL ISSUES OF NATURAL ESTER FLUIDS

In the following section are considered the most typical issues of Natural Ester fluids as their chemical composition, the most common values for their properties and their environmental impact.

A. Composition

Natural ester fluids usually come on its native form derived from soybean extracting oil processes. This natural ester consists of a mixture of fatty acids and saturated (without C-C double bonds) and unsaturated (with C-C double bonds) esters. Fig. 1 shows the main molecular structure of several natural esters of native soybean oil. The percentage of unsaturated compounds in the mixture confers the dielectric and viscosity properties to the natural ester. It has been evidenced in [7], [8], where the more unsaturated compounds in the oil the more susceptible to degradation by oxidation and hydroxylation reactions. Additionally, it has been found that the increase in temperature and traces of iron (Fe) and copper (Cu) accelerates the oxidation processes. The most notable consequences resulting from the oxidation are 1) the decomposition products such as alcohols, aldehydes, ketones and acids, 2) the increase in the acidity, 3) the formation of polymerization products and 4) the increase in oil viscosity.

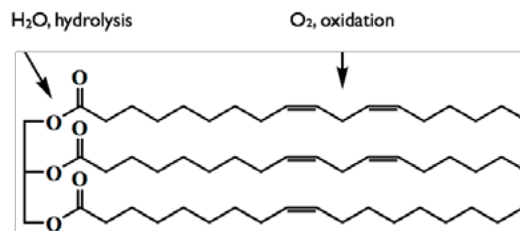


Fig. 1. Natural ester fluids molecular structure. Indicates the atoms which can carry out oxidation and hydrolysis reactions

Also, moisture, oxygen and environmental pollution deteriorate the dielectric characteristics [9], [10]. Moisture and environmental pollutants reduce the dielectric strength of the fluid, while the oxygen atmosphere accelerates the processes of formation of sludge mainly formed by the decomposition of oils. To prevent or lessen all these degradation processes, it has been incorporated some additives to the natural ester fluids. Have been used mainly three types of additives:

Oxidation inhibitors: these compounds reduce the formation of resins, acids and polymers. These inhibitors are used gradually and must be renewed. Examples include the butylated hydroxyl toluene and the anisole in a ratio of 0.1 – 3.0 %.

Metal deactivators: these substances protect the metal surfaces to prevent corrosion. For example, to reduce reactions taking place in a Cu surface, benzotriazole derivatives are added in a proportion not exceeding 1.0 %.

Freezing point depressants: these substances reduce the freezing point which usually tends to be higher in mineral than in natural esters. These substances vary depending on the type of oil and producer. As shown in figure 2, the conventional process consists of a partial hydrogenation of fatty acids and esters in order to reduce the number of insaturations and therefore reduce the freezing point.

Furthermore, in Table 4 summarizes some characteristics in the composition of canola oil Rapsol-T, [11]. It serves as a source for the production of natural ester fluids used in the world market.

B. Properties

Since its development, vegetable dielectric oils have been characterized by various physical and chemical tests to determine a direct relationship between their properties and performance [12]. In Fig. 2. Hydrogenation reaction of fatty acids and esters. Metal-based catalysts accelerate the partial hydrogenation

TABLE 4. PROPERTIES OF RAPSOL T CANOLA OIL [11]

Characteristic	Value
% palmitic acid	4.8
% stearic acid	1.6
% oleic acid	60.0
% linoleic acid	21.2
% linolenic acid	9.8
Cloud point (°C)	0
Flash point (°C)	> 220
Acidity (mg KOH/g)	< 0.1
% antioxidants	0.1
% metal deactivators	0.02

Table 5 is shown the most relevant characteristics of various insulating fluids and the corresponding test method. Furthermore, although the literature has studied a wide variety of properties of natural ester fluids, this article describes the basis of three most improved properties respect to the mineral oil: resistance to ignition, impact on the aging of insulating papers and the impact on the environment. This latter property will be discussed in section C.

Ignition resistance: among the main consequences of aging infrastructure of transformers, at least in Colombia, is the increase in the number of electrical faults. A smaller but still significant percentage of such failures found in transformer substations are considerable and often results in the burning of oil in which the transformer is immersed, and hampers extinction. These cremations can be prevented using vegetable dielectric oil, which are recognized as less flammable according to the “National Recognized Testing Laboratory” of USA [13].

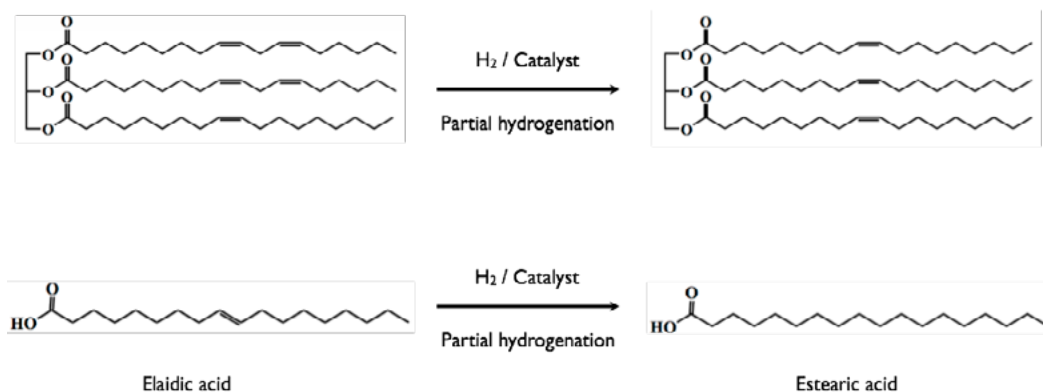


Fig. 2. Hydrogenation reaction of fatty acids and esters. Metal-based catalysts accelerate the partial hydrogenation

TABLE 5. CHARACTERISTICS OF SOME INSULATING FLUIDS

Characteristic	FR3	R-TEMP	Conventional oil	Silicon oil	Synthetic esters	Test method
Dielectric strength (kV)	56	52	45	35-70	45 a 70	ASTM D877
Viscosity 40°C	33	113	9,2	39	14 a 29	ASTM D455
Viscosity 100°C	8	12	2,3	17	4 a 6	ASTM D445
Fire point (°C)	324	276	147	300	250 a 270	ASTM D92
Flash point (°C)	360	312	165	343	300 a 310	ASTM D92
Pour point (°C)	-21	-22	-50	-55	-40 a -50	ASTM D97
Density (kg/dm ³)	0,92	0,87	0,87	0,96	0,9 a 1,00	ASTM D1298
Specific hot (J/g·K)	2,09	1,88	1,63	1,5	1,8 a 2,3	ASTM D1269
Thermal conductivity (W/m·K)	0,17	0,13	0,11-0,16	0,16-0,17	0,15	CPS
expansion coefficient (10 ⁻⁴ /K)	7,4	7,3	7-9	10	6,5 a 10	CPS

The most critical property for determining the ignition resistance of the transformer fluids is the fire point. When immersed transformer is operating at full load, with an ambient temperature of 40 °C, the insulating fluid temperature is about 100 °C. Then, when electrical protective equipment does not work as expected, warming caused by an internal failure or chronic overload can increase the fluid temperature, which also causes the oil ignition. In mineral oils this phenomenon occurs with moderate rate while, conversely, in natural esters the fire point is much higher (typically above 300 °C), in which the ignition is virtually impossible under conditions actual operation of the transformer [14].

Table 6 shows the self-ignition temperatures of most used natural ester fluids in transformers (the self-ignition temperatures are about 50 °C higher than the fire point) [15]. The ignition mechanism begins with an excessive heating of the fluid, thereby keeping vapor concentration increases significantly. Thus, initially the vapor is incinerated and then the combustion is maintained on the surface of the fluid. Other properties related to ignition resistance are self-extinction, ignition by electric current, the hot metal ignition and self-ignition. All these properties are improved by insulating oils of vegetable origins [16].

TABLE 6. SELF-IGNITION TEMPERATURES BY THE ASTM 659

Oil	Self-ignition temperatures (°C)	
	Range	Average
Mineral oil	225-228	226.5
R-Temp	357-360	358.5
Envirotemp 200	373-376	374.5
Silicon oil DC 561	399-402	400.5
Envirotemp FR3	401-404	402.5

Impact on the aging of insulating papers: it has been performed some test on a laboratory scale in which is evaluated the aging of the insulating papers used by conventional transformers. [17] have found that aging by thermal degradation of Kraft paper is considerably slower in natural ester than in mineral oil under the same thermal conditions. In tests on sealed containers at 170 °C, paper aged in natural ester takes 5-8 times longer to reach the end-of-life point that the paper aged in mineral oil.

The test results also allow estimating that 110 °C, approximated operation temperature of the transformer, the end-of-life point of the paper immersed in natural ester is 2.5 times larger than the paper submerged in mineral oil. Since the paper is essentially cellulose, clearly there is a marked decrease in the thermal aging of the cellulose in natural ester dielectric fluids. It has been proposed two types of protection provided by the natural ester that improves the aging characteristics of cellulose: water sweeping and steric protection to the hydrolytic reactions of cellulose.

Water sweeping works in two ways. 1) At high temperatures, the natural ester can cause hydrolysis, removing water molecules from cellulose and thus reducing potential harm caused by water. 2) Natural ester can capture considerably more water than mineral oil. At room temperature, water saturation of the natural ester is 1050 mg/kg, while for mineral oil is 60 mg/kg, i.e., natural ester can absorb more water than the mineral oil, hence the former has a greater drying effect on the paper and thus decrease its aging [18].

On the other hand, the hydrolytic protection is carried out because natural ester can interfere with the process of cellulose hydrolysis due to thermal stress. Natural ester reacts with OH groups and terminal chains through a mechanism known as transesterification. Esterification's of the reactive OH sites of the cellulose with bulky steric groups stabilize the molecule and extend the life of the insulating paper [19].

C. Environmental impact

At present, the environmental impact caused by electrical processing equipment using mineral oil or some synthetic oils such as silicone or other hydrocarbons of low biodegradability is the subject of wide interest, especially when these apparatus are located in populated areas, in malls, parks or nearby watersheds. Most environmental surveillance agencies consider that spills of these oils are harmful to humans and the other living species.

Among the different factors that identify the environmental impact of dielectric oils are the biodegradability, thermal decomposition, oxidative degradation and arcing [20]. Biodegradability has been reported in the method CEC L-33 -A-94, where was found that the natural ester fluids have a 97 % of biodegradability, while the mineral oils have only 30 % when applied the same method. Thermal decomposition is similar in both species of dielectric oil. It basically produces carbon dioxide (CO₂), carbon monoxide (CO), hydrogen (H₂) and some hydrocarbons.

IV. CONCLUSIONS

The use of natural ester fluids in electrical equipment brings some advantages not only in terms of equipment performance but also in terms of environmental impact. At the international level there are some ASTM standards governing the use of natural ester fluids on electric devices. However, in Colombia there is currently no rule governing the application of this technology. Current regulations are based on the application of mineral ester fluids with specific restrictions on the use of PCBs. This situation is an important point of analysis and towards which we can drive future researchers.

Regarding to the advantages of the application of natural esters, this paper summarizes the most relevant physicochemical characteristics to provide better performance. The ability to absorb more water than mineral oils (up to 1050 mg/kg), its high fire point (greater than 300 °C) and the flexibility to be combined with other compounds that allow inhibit oxidation, deactivate metals and reducing point freezing are features that provide better performance in electrical equipments.

On the other hand, it has been discussed the biodegradability of natural esters. The works reported in the literature indicate that natural esters degrade up to 97 % within a remarkably short time, i.e., have a significantly shorter half-life. Also, the gas emission is reduced 1/4 by Natural Ester Fluids respect to Mineral Ester Fluids.

V. PERSPECTIVES

This survey results from a pilot project, which evaluate the performance of conventional transformers immersed in natural ester fluids. From these results will be extracted knowledge to the creation of a new prototype specially adapted to the natural ester fluid refrigerant and climatic conditions of the main cities of Colombia.

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