World Academy of Science, Engineering and Technology
International Journal of Electrical and Computer Engineering
Vol:15, No:6, 2021

Study of Compatibility and Oxidation Stability of Vegetable Insulating Oils

Helena M. Wilhelm, Paulo O. Fernandes, Laís P. Dill, Kethlyn G. Moscon

***Abstract*—**The use of vegetable oil (or natural ester) as an insulating fluid in electrical transformers is a trend that aims to contribute to environmental preservation since it is biodegradable and non-toxic. Besides, vegetable oil has high flash and combustion points, being considered a fire safety fluid. However, vegetable oil is usually less stable towards oxidation than mineral oil. Both insulating fluids, mineral and vegetable oils, need to be tested periodically according to specific standards. Oxidation stability can be determined by the induction period measured by conductivity method (Rancimat) by monitoring the effectivity of oil's antioxidant additives, a methodology already developed for food application and biodiesel but still not standardized for insulating fluids. Besides adequate oxidation stability, fluids must be compatible with transformer's construction materials under normal operating conditions to ensure that damage to the oil and parts of the transformer does not occur. ASTM standard and Brazilian normative differ in parameters evaluated, which reveals the need to regulate tests for each oil type. The aim of this study was to assess oxidation stability and compatibility of vegetable oils to suggest the best way to assure a viable performance of vegetable oil as transformer insulating fluid. The determination of the induction period for several vegetable insulating oils from the local market by using Rancimat was carried out according to BS EN 14112 standard, at different temperatures (110, 120, and 130 °C). Also, the compatibility of vegetable oil was assessed according to ASTM and ABNT NBR standards. The main results showed that the best temperature for use in the Rancimat test is 130 °C, which allows a better observation of conductivity change. The compatibility test results presented differences between vegetable and mineral oil standards that should be taken into account in oil testing since materials compatibility and oxidation stability are essential for equipment reliability.

***Keywords*—** Compatibility, Rancimat, natural ester, vegetable oil.

I. Introduction

Mineral insulating oils (MIO) are the most widely used fluids for electrical insulation due to their adequate dielectric characteristics that have been improved throughout the 20th century to meet electric sector requirements. Nevertheless, mineral oils, besides being non-renewable, pose environmental risk in the case of spills that can contaminate both soil and groundwater. Currently, there is a great concern regarding environmental preservation, which has encouraged the use of biodegradable insulating fluids, such as natural and synthetic esters [1], [2].

Natural insulating esters consist of triacylglycerol molecules, that are biodegradable and non-toxic. For the electricity sector, Natural Insulating Esters (NIE) also have the advantage of their high flash and combustion points, ensuring fire protection during use. On the other hand, NIE are more easily oxidized fluids than MIO. This is due to fluid composition, since NIE is composed of triacylglycerols (esters) and MIO contains basically hydrocarbon compounds. MIO oxidation produces acidic compounds responsible for accelerating insulating paper degradation. Despite being less stable to oxidation, NIE forms degradation products less aggressive to insulating paper, as they are weaker acids than those released by MIO [1]-[3].

Oxidation induction time test is common for ester derivatives. Conductivimetric method (Rancimat method) is an alternative to determine insulating ester oxidation induction period. Rancimat method is widely used in food sector and for pure biodiesel, the latter using BS EN 14112 standard method. Some researchers have proposed to use Rancimat to assess NIE induction period. Methodology is based on monitoring of a distilled water sample that receives volatile oxidation compounds generated from an analyzed sample that is under accelerated aging test. Induction period is characterized by the time to sudden high increase in water conductivity, which corresponds to time that sample withstands to test conditions. Rancimat has been a suitable method for determining this insulating ester property [4]-[6].

Another important parameter to be evaluated in insulating fluids is their compatibility with transformers construction materials. Compatibility test is carried out to ensure that there is no damage to oil and transformer parts under normal operating conditions due to interaction between them. In the literature, it is commonly reported the use of MIO compatibility standard (ASTM D3455) for the vegetable oil compatibility evaluation [7]. Brazil was a pioneer in testing and standardizing vegetable insulating oils' compatibility, by means of standard test method ABNT NBR 16431. In compatibility tests it is considered that variation in vegetable insulating oil dielectric properties is essential to determine oil contamination with transformer parts material. Both ASTM and Brazilian normative consider determination of these oil parameters: total acid number, color and dielectric loss; but they differ in other evaluated parameters, since ABNT includes oil viscosity and dielectric strength. Brazilian standard is being revised and the inclusion of DGA (dissolved gas analysis) is under discussion [7], [8].

The aim of this study is to evaluate the importance of NIE properties namely, oxidation induction period by Rancimat method using different temperatures (110, 120 and 130 °C) and insulating fluid materials compatibility with transformers construction materials.

Laís Pastre Dill is with the Department of Research and Innovation of VEGOOR, Colombo, Paraná, Brazil (e-mail: lais@vegoor.com.br).

II. Material and Methods

A. Induction Period Determination

Induction period for four NIE from local market, namely, NIE1, NIE2, NIE3 and NIE4, using Rancimat equipment (model 743) was performed according to BS EN 14112 standard, at different temperatures (110, 120 and 130 °C). Analysis is carried out in dry atmospheric air with a 10 L/h flow and at the end of test, induction period was calculated.

B. Compatibility Tests

Vegetable oil compatibility was determined according to ASTM D3455 and ABNT NBR 16431 standards, using materials from transformer construction, such as silicon steel, paint, rubber, glue, and paper provided by distinct local suppliers. Gasket materials, in this case rubbers, were tested in a revised rubber to oil ratio, which was 6 cm^2 per 800 mL of oil. Previous standard gasket material:oil ratio was 65 cm^2 surface area per 800 mL of oil (ASTM D3455 and ABNT NBR 16431).

DGA was performed by oil accelerated aging inside a syringe, this method consists of preparing material test samples of specific sizes and insert in a glass syringe that is filled with 40 mL of insulating vegetable oil. A blank test (without materials) is carried out simultaneously, which is a syringe containing only 40 mL of insulating vegetable oil. Both syringes are aged in an oven at 100 °C for 164 h and the test is performed in duplicate, followed by the measurement of DGA.

III. Results and Discussion

A. Determination of Induction Period

Induction period, determined as described above, for four NIE at three different temperatures are presented in Table I.

TABLE I
Induction Period for NIE at Different Temperatures

Natural Ester	Induction Period (h)		
	110 °C	120 °C	130 °C
NIE1	9 ± 1	4 ± 1	3 ± 1
NIE2	18 ± 1	9 ± 1	6 ± 1
NIE3	52 ± 1	25 ± 1	14 ± 1
NIE4	8 ± 1	4 ± 1	3 ± 1

Induction period values allowed to rank oxidation stability of tested NIE as NIE 3 > NIE 2 > NIE 1 ~ NIE 4. This result is related to chemical composition of ester profiles, in addition to type and quantity of additives used by manufacturers or suppliers of each natural ester. Figs. 1-4 show conductivity versus time for tested NIE in each temperature evaluated.

Induction period of NIE is dependent on test temperature. Different temperature tests enable to observe that the higher the test temperature, the shorter the induction period, that is, the shorter the time required to induce NIE oxidation.

Conductivity versus time curves indicated that 130 °C favored visualization of sharp conductivity increase compared to 110 °C, except for NIE4, where induction period for each temperature was remarkably similar.

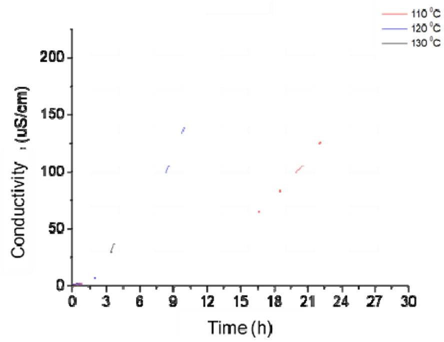

Fig. 1 Conductivity *vs.* time curve for NIE1 at 110 °C, 120 °C and 130 °C

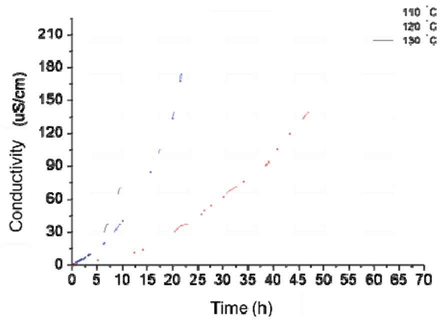

Fig. 2 Conductivity *vs.* time curve for NIE2 at 110 °C, 120 °C and 130 °C

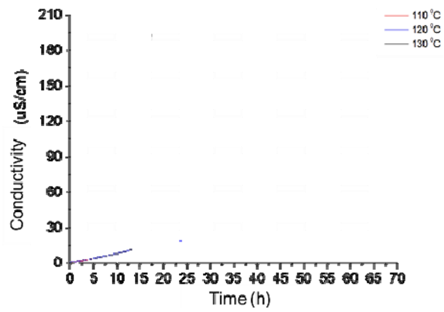

Fig. 3 Conductivity *vs.* time curve for NIE3 at 110 °C, 120 °C and 130 °C

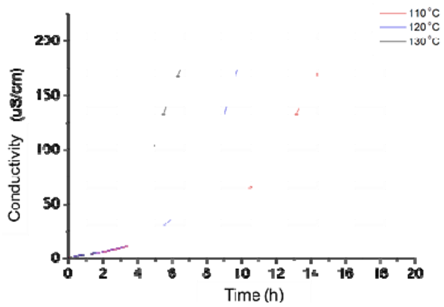

Fig. 4 Conductivity *vs.* time curve for NIE4 at 110 °C, 120 °C and 130 °C

B. Compatibility Tests

All compatibility tests are performed using NIE 4 due to its higher spread in local market. Standard method ABNT NBR 16431 prescribes that NIE compatibility is determined by variation limits for physicochemical parameters of NIE after test (using transformer construction materials) in relation to the blank test, that is, only NIE. These limits are shown in Table II and, when sample reaches these limit values, it is called incompatible.

TABLE II
LIMITS (VARIATION) ALLOWED OF OIL PHYSICOCHEMICAL PARAMETERS IN COMPATIBILITY TESTS OF ABNT NBR 16431

Parameter	Standard test method	Limits (max)
Dielectric loss	ABNT NBR 12133	3%, increase.
Total acidity number	ABNT NBR 14248	0.03 mg KOH/g, increase.
40 °C Viscosity	ABNT NBR 10441	0.4 cSt, increase.
Color	ABNT NBR 14483	0.5, increase.
Dielectric strength	ABNT NBR IEC 60156	10%, decrease.

[a] Determined at 90 °C.

Standard test method ASTM D3455 does not prescribe limits on physicochemical parameters that tested insulating oil may vary after testing (using transformer construction materials) in relation to a blank sample. ASTM provides maximum values that blank test shall present (Table III) and when tested sample shows any variation towards these values, it is classified as incompatible.

TABLE III
ASTM D3455AGED OIL SPECIMEN REFERENCE PROPERTIES

Parameter	Standard method	Value*
Dielectric loss factor[a]	ASTM D924	1.1%, max.
Total acid number	ASTM D974	0.03 mg KOH/g of sample, max. increase
Interfacial tension	ASTM D971	38 mN/m, min
Color	ASTM D1500	0.5, max. increase
Dielectric strength	ASTM D877	28 kV, min.

[a] Determined at 100 °C.
* ASTM standard considers typical values for most of the mineral oils currently in the market.

Physicochemical parameter results obtained for blank test and for test materials after standard compatibility test are presented in Table IV, while Table V shows compatibility diagnosis obtained for each material in NIE, regarding both standards, ASTM D 3455 and ABNT NBR 16431.

Considering that NIE usually presents a high dielectric loss when compared to MIO, dielectric loss factor of blank NIE was considered adequate, since it met ASTM D6871 standards, which regulates specifications for natural ester fluids used in electrical apparatus and provides dielectric loss factor of NIE (at 100 °C) as 4.0% maximum.

Paper was the only tested material classified as fully compatible with NIE toward both standards, ASTM and ABNT, since NIE physicochemical parameter variations for this material are not as significant as for other test specimens.

Total acid number exceeded variation limits when using glue, being incompatible for both standards (ASTM and ABNT). However, MIO releases acidic compounds that are known to be more aggressive than those formed by NIE. Therefore, total acid number limit when considering NIE shall be further discussed.

TABLE IV
PHYSICOCHEMICAL PARAMETERS OF NIE EXPOSED TO DIFFERENT MATERIALS IN COMPATIBILITY TEST

Material	Parameter			
	Dielectric loss at 90 °C (%) *	Total acid number (mg KOH/g of sample)*	Viscosity at 40 °C (cSt)*	Dielectric strength*
Blank	1.6	0.02	32.0	49.4
Silicon Steel	2.2	0.02	32.8	-
Paint 1[a]	3.4	0.02	32.7	49.3
Paint 2[b]	1.9	0.02	32.6	49.2
Rubber	5.6	0.05	33.1	-
Glue	1.8	0.09	33.9	-
Paper	1.5	0.02	32.1	49.8

* Average values obtained from triplicates.
[a] Monocomponent paint.
[b] Bicomponent paint.

TABLE V
COMPATIBILITY DIAGNOSIS OF DIFFERENT MATERIALS IN NIE REGARDING ASTM AND ABNT STANDARDS

Material	Parameter variation			
	Dielectric loss factor at 90°C*	Total acid number*	Viscosity at 4°C*	Dielectric strength (kV)*
Silicon Steel	Compatible (ASTM/ABNT)	Compatible (ASTM/ABNT)	Incompatible (ABNT)	-
Paint 1[a]	Compatible (ASTM/ABNT)	Compatible (ASTM/ABNT)	Incompatible (ABNT)	Compatible (ASTM/ABNT)
Paint 2[b]	Compatible (ASTM/ABNT)	Compatible (ASTM/ABNT)	Incompatible (ABNT)	Compatible (ASTM/ABNT)
Rubber	Incompatible (ASTM/ABNT)	Compatible (ASTM/ABNT)	Incompatible (ABNT)	-
Glue	Compatible (ASTM/ABNT)	Incompatible (ASTM/ABNT)	Incompatible (ABNT)	-
Paper	Compatible (ASTM/ABNT)	Compatible (ASTM/ABNT)	Compatible (ABNT)	Compatible (ASTM/ABNT)

* Average values obtained from triplicates.
[a] Monocomponent paint.
[b] Bicomponent paint.

Tested rubber resulted incompatible due to dielectric loss both in ASTM and ABNT standards, even when measuring loss at 90 °C, instead of the ASTM prescribed temperature of 100 °C. This affirmation can be made, because the dielectric loss increases with temperature and the value obtained at 90 °C is already above ASTM D6871 prescribed maximum. It is important to highlight that this result was achieved using rubber to oil ratio revised and lowered in relation to the prescribed by the standards.

Kinematic viscosity, that is only included in ABNT standard, presented variation for almost all tested materials, which can be related to the narrow limit range imposed by standard (0.4 cSt). Results confirm the importance of performing triplicate tests to ensure that viscosity variation is only due to the tested material contaminating NIE and not because of oxygen entry in test vessels. In addition, it is important to have viscosity as an evaluation parameter for compatibility tests since it enables assessment of sealing control during experiments. Also, viscosity variation limit needs to be revised, for currently range is close to experimental error.

Some paper and paint samples were analyzed by DGA and results are shown in Table VI.

TABLE VI
DISSOLVED GAS ANALYSIS

Gas (ppm)	Sample*			
	Blank	Paint 1[a]	Paint 2[b]	Paper
H_2	66	89	81	96
CH_4	1	2	3	2
CO	31	142	48	38
CO_2	412	454	737	443
C_2H_6	51	58	68	57
C_2H_4	2	5	3	2
C_2H_2	0	1	0	0
CO_2/CO	13	3	15	12

*Average values obtained from triplicates.
[a] Monocomponent paint.
[b] Bicomponent paint.

DGA indicates that tested paints led to different results from the blank sample, which may suggest a contrasting interaction with NIE; although, paint 1 and paint 2 were similar regarding physicochemical analysis. Also, paints were some of the tested materials that significantly altered NIE physicochemical parameters. It is pointed out the importance of evaluating various composition painting to assess insulating fluid compatibility.

Using of DGA as an additional parameter for monitoring insulating fluids' compatibility shall be discussed, since acceptable gas level variations in relation to the blank sample need to be better evaluated. Therefore, it is suggested that further studies involving several materials from different compositions be performed to discuss the usefulness of DGA as an auxiliary method to assess insulating fluid compatibility.

IV. CONCLUSION

This study demonstrated the feasibility of using Rancimat method to monitor NIE oxidation induction period as well as that the best test temperature is 130 °C.

Regarding compatibility tests, it is suggested further discussion of total acid number and viscosity limits for NIE, considering the nature of acid oxidation compounds and its effects on oil condition and transformers aging. Accepted variation values shall also be evaluated regarding experimental measurement errors. Furthermore, DGA analysis shall be better evaluated as a tool for insulating fluid compatibility tests.

Differences between vegetable and mineral oils shall be taken into account in compatibility tests procedures and results, since distinct properties variation resulting from oil contamination and degradation can be observed, which is fundamental when choosing transformers construction materials for different insulating oils.

REFERENCES

[1] C. P. McShane *Vegetable-oil-based dielectric coolants*. IEEE Application Magazine, 2002.
[2] L. R. Lewand, *Natural ester dielectric liquids*. Chemist's Perspective. Neta World, 2004.
[3] H. M. Wilhelm, M. B. C. Stocco, L. Tulio, "Edible natural ester oils as potential insulating fluids". *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 20, pp. 1395-1401, 2012.
[4] H. M. Wilhelm, G. B. Stocco, S. G. Batista Jr., "In-service natural ester-based insulating fluids reclaiming: preliminary study", *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 20, pp.128-134, 2013.
[5] H. M. Wilhelm, L. Feitosa, L. L. Silva, N. A. G. Gomèz, A. Cabrino, P. Ramos, "Evaluation of in-service oxidative stability and antioxidant additive consumption". *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 22, pp. 864-869, 2015.
[6] H. M. Wilhelm, P. O. Fernandes, L. G. Feitosa, G. C. dos Santos, G. Dal Pont, "Determination of the oxidation induction time of mineral insulating oils using a modified EN 14112 Method". *IEEE Electrical Insulation Magazine,* vol. 34, pp. 7-14, 2018.
[7] H. M. Wilhelm, V. Franch, L. Tulio, A. F. Franch, "Compatibility of Transformer Construction Materials with Natural Ester-based Insulating Fluids". *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 22, pp. 2703-2708, 2015.
[8] H. M. Wilhelm, L. Tulio, W. Uhren, "Produção e uso de óleos vegetais isolantes no setor elétrico". *Brasil Engenharia*, vol. 592, pp. 120-124, 2009.