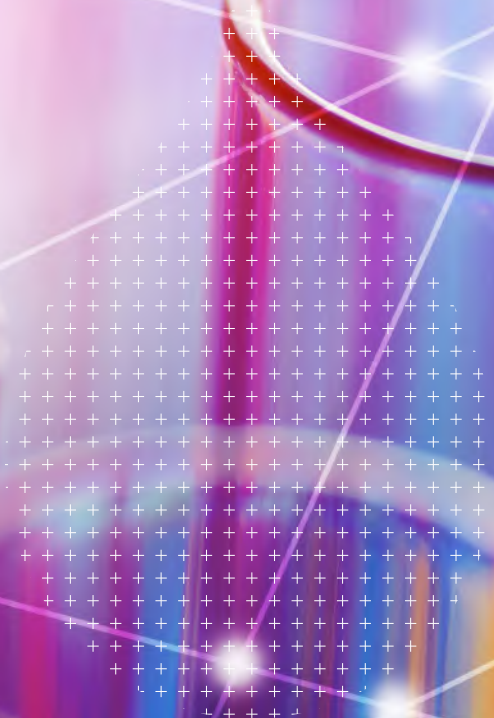


A Critical Evaluation of Natural Esters for Application in Transformers

Due to the depletion of the mineral oil source and environmental impacts, the transformer industry has shifted its focus from petroleum-based mineral oil to natural and synthetic esters. Ester fluids have been present on the scene for quite some time now, and the environmental advantages and availability have the industry moving towards this avenue more strongly as time passes. The gradual move to the use of natural and synthetic esters is additionally supported by more data that is forthcoming from industry-based studies that are focused on using these fluids in electrical equipment.

This article will focus on environmental concerns, fire safety, physio-chemical properties, and thermal and dielectric performance of natural esters.

Finally, we will discuss the fundamental properties of natural esters and material compatibility related to electrical design.



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Corné Dames is the Managing Director of Independent Transformer Consultants, always striving to keep on top of new developments and research. She has expertise as Laboratory Manager in the analysis of transformer oils and as diagnostician identifying problem areas in transformers, as well as profiling of transformers according to available results thus empowering the customer to take preventative steps in maintenance. Corné has vast practical and theoretical knowledge on reliability maintenance programs. Coming from a strong chemical background she has insight in all the chemical processes that are part of the transformer system. Coupled with technical insight, her knowledge and experience help customers optimize their reliability maintenance and electrical asset lifetime.



Introduction

In a transformer, the liquid-cellulose system forms the main component of insulation. This system has a trifold role as the dielectric barrier, mechanical support and heat dissipation route. The insulating liquid is the backbone of the entire system, as this part will have a tremendous impact on the transformer's achieved lifetime [1]. The insulating fluid in a transformer has three functions – to electrically insulate the active parts, to transfer heat from the conductors to the radiators, and to provide a diagnostic medium which enables engineers to assess the equipment's health through regular monitoring and analytical means. Additionally, the insulating liquid is used for arc quenching (in tap changers, for instance) and as an acoustic dampener. Both arc quenching and acoustic dampening are essential for lifetime optimization.

One of the significant concerns related to the use of mineral oil is its flammability. A dramatic escalation of power demand over the past few years has led to overloaded electrical grids, resulting in failures, fires, and consequent oil spills, for which government regulatory agents are imposing stiff penalties due to their environmental impact. Mineral oils may have a toxic effect on the environment that will impact that area for many years to come. Having poor biodegradable properties, serious mineral oil spills can contaminate the soil and our waterways. Additionally, fire hazards are a real threat when using mineral oils, especially in densely populated areas.

As petroleum sources are depleting, the threat of shortages is becoming a reality. To ensure that ester fluids are used continuously and across many applications, we need to guarantee the reliability and safety of electrical equipment.



Chemistry and the Emergence of Insulating Fluids

Natural esters are extracted from crops like soybean, sunflower, rapeseed (canola), flax, olive, poppy, etc.

International Standards

There is an increase in the use of natural esters in the transformer industry. They are currently used primarily in distribution and medium power transformers, in new units, and for retro-fill units. The first large power transformer of 420 kV voltage class was filled with natural ester fluid back in 2013, in the south of Germany, nearby Stuttgart. Currently, there are around 30-40 units in this voltage class that are already energized or in the process of production, including projects in Spain and Italy.

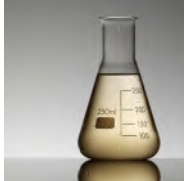
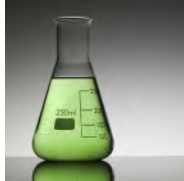
Properties	Standard	Mineral Oil	Natural Ester
Material used	-	Petroleum crude oil	Crops, sunflower, soybean, etc.
Principle components	-	Complex mixture of hydrocarbons	Plant based natural ester
Chemical composition	-	$ \begin{array}{cccccccc} & H & H & H & H & H & H & H \\ & & & & & & & \\ H & -C & -C & -C & -C & -C & -C & -C \\ & & & & & & & \\ & H & H & H & H & H & H & H \end{array} $	$ \begin{array}{c} O \\ \\ CH_2-O-C-R^1 \\ \\ CH-O-C-R^2 \\ \\ O \\ \\ CH_2-O-C-R^3 \end{array} $
Visual examination	ASTM D 1524	Clear and light	Clear and light
Color	ASTM D 1500	Pale Yellow	Pale Green
Color	IEEE	0.5	<=1
Appearance of liquid			

Table 1. Basic properties of insulating liquids: mineral oil and natural ester [2-6]



Physio-chemical Properties

Acidity accelerates the oxidation process in mineral oil and in cellulose systems. In the presence of moisture, the acid can cause rust on the iron components in the transformer.

The acids in mineral oil are mostly short-chain carboxylic acids that are formed during the degradation process of mineral oil. These acids are more aggressive, having an essential impact on paper lifetime.

Natural esters have a higher inherent acid content, but they are long-chain free fatty acids that are very mild for other materials and soluble in the natural ester. For instance, the formed acids include the well-known "omega-3", which is used as a medicine for reducing cholesterol levels.

The interfacial tension (IFT) of a liquid is defined as the measure of the force required to break through an interface between water and oil, thus related to the molecular attraction/repulsion forces between them. Interfacial tension is a significant indicator of polar contaminants and oil decay products in mineral oil. New mineral oils generally have a relatively higher interfacial tension than new natural ester fluids. The lower variation of the IFT in natural esters does not affect the fluid performance, but it limits the use of IFT as an indicator of fluid degradation.

Fire Point and Flashpoint

The fire point and flashpoint are the measures of the resistance of the liquid to catching fire.

The flashpoint is defined as the lowest temperature at which the vapor pressure is sufficient to form an ignitable mixture with air near that liquid's surface.

The fire point is the lowest temperature at which a liquid in an open container will attain a vapor pressure sufficient to continue to burn once ignited.

Mineral oil has a much lower flashpoint and fire point than ester fluids. A fire point of more than 300°C is required to classify a liquid as "less flammable".

Up to date, no cases of transformer fires have been reported involving natural ester liquid.

Environmental Impacts

The threat of depletion of crude oil sources is an ever-increasing reality. Exhaustion of mineral oil would lead to severe problems in many areas of the petroleum industry. That said, petroleum products are poorly biodegradable, and they pollute the soil and waterways when spills occur. In densely populated areas, mineral oil filled transformers pose a risk due to the fire hazard and potential environmental issues.

Water Saturation

Water has a detrimental effect on the transformer's overall life and on the electrical properties of the insulating liquid which needs to act as a barrier to ensure there is no electrical flashover. A high moisture concentration in mineral oil leads to visible effects as the oil will seem to be "murky", not clear.

Because natural esters are more hygroscopic than mineral oils, having a saturation point 10-15 times higher than

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Mineral Oil	Natural Ester
IEC 60296 - Edition 4 -2012-02, Fluids for Electrotechnical Applications – Unused Mineral Insulating Oils for Transformers and Switchgear	IEC 62770 - Edition 1.0 - 2013-11, Fluids for Electrotechnical Applications – Unused Natural Esters for Transformers and Similar Electrical Equipment
ASTM D3487-09 – Standard Specification for Mineral Insulating Oil Used in Electrical Apparatus	ASTM D6871-17, Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus
IEEE STD C57.106-2006, IEEE Guide for Acceptance and Maintenance of Insulating Oil in Equipment	IEEE STD C57.147-2008, IEEE Guide for the Acceptance and Maintenance of Natural Ester Fluids in Transformers

Table 2. List of available international standards on different insulating oils [4, 5, 7, 8, 9, 10]

that of mineral oil, we cannot apply the same moisture content limits. Even with significant amounts of moisture, the ester fluid can still retain its dielectric properties. It should be noted that the effect of water content on dielectric strength as a function of percent of saturation is the same for mineral oil and natural ester fluids [11, 12].

Oxidation Stability

An insulating liquid is prone to oxidation due to the presence of carbon-carbon double bonds. In natural esters, there is a higher concentration of carbon-carbon double bonds in each molecule. Therefore, natural esters are more prone to oxidation than mineral oils. This oxidation process is irreversible but inhibited by the use of antioxidants in the product formulation. In this process, oxygen will be consumed and incorporated into the product of the chemical reaction. When natural esters are continually exposed to oxygen, complex molecules will be formed, increasing their viscosity. This can also lead to oxygen formation containing byproducts such as alcohols, aldehydes, ketones and acids. Therefore, it is vitally important to minimize oxygen exposure during the manufacturing process and while the liquid is used in a transformer. Using sealed units will prevent exposure to oxygen. A diaphragm barrier is required for large transformers with conservators between the internal and external venting or a nitrogen headspace barrier.

Density

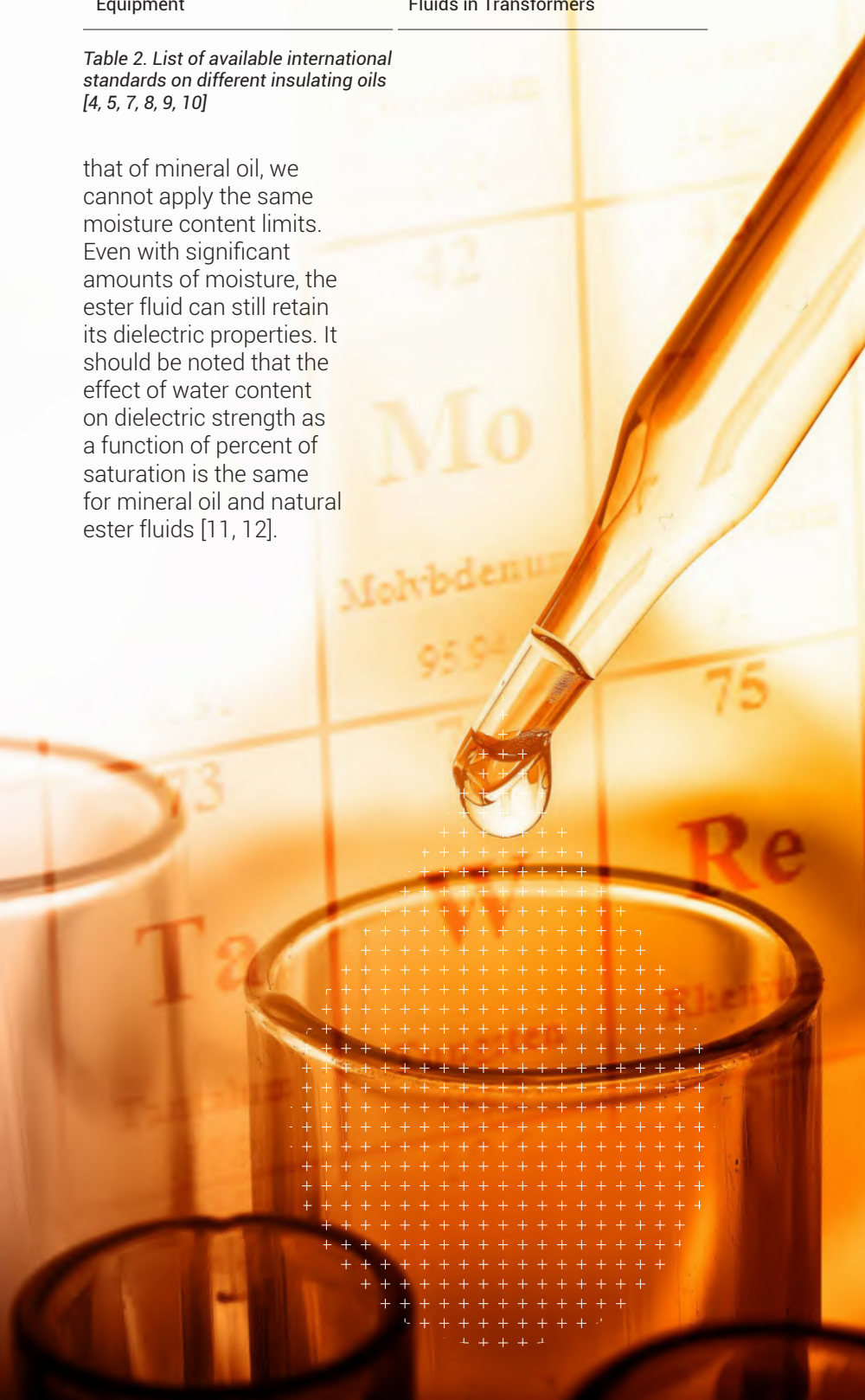
The relative density is stipulated as the ratio of the weights of equal volumes of liquid and water at 15°C. Mineral oil (<0.91 g/ml at 15°C) has a lower relative density than natural esters (<0.92 g/ml at 25°C) as per the IEEE standard method.

Pour Point

The pour point of standard mineral oil is typically lower than -40°C, while the pour point of natural esters is in the range of -15°C to -25°C.

Dissolved Gas Analysis (DGA) and Stray Gassing

Stray gassing is defined as the formation of gases when insulating oils are heated at relatively low temperatures (90-200°C) [13]. A substantial quantity of stray gasses, like hydrogen and ethane, is observed in natural ester for some time after energizing a transformer, which can last for months. The susceptibility to stray gassing can differ from batch to batch [14].



Natural esters have a lower gas generation in partial discharge phenomena (hydrogen and methane formation with traces of acetylene) than mineral oil at the same voltage level.

Effect of Concentrated Heat Flux

The insulating fluid is heated to ensure an increased impregnation rate of the cellulose insulation. The insulating liquid is prepared in the heat exchanger chamber of the filtration unit. Excessive heat flux harms the dielectric dissipation factor. Natural ester has a higher thermal limit than mineral oil to initiate phase change. Due to their higher viscosity, ester fluids will remain in contact with the heating element for a more extended period than mineral oil. This means that the maximum allowable watt density for exposure is lower for natural esters. A solution to this would be to limit the maximum watt density or heat flux density, or to avoid immersion heaters instead of turning to plate-to-plate heat exchangers to increase the heating surface and reduce the concentrated heat flux.

Change in Fluid Properties

The application of natural ester fluids is monitored in a wide application range in order to track the changes in the fluid properties under actual service conditions. These results compare well with those found in the accelerated aging experiments done under laboratory conditions. Natural ester exhibits changes during the aging process similar to those seen in mineral oil.

As the natural ester ages, the dissipation factor as well as the acid value will increase, while the interfacial tension and resistivity will decrease [15].

Conclusion

Natural ester has been available for decades. In the transformer industry, it has been established that natural ester is safely applied in distribution transformers and other transformer applications. More than 10,000 distribution transformers using vegetable ester fluids ranging from 10 kVA to 10 MVA are currently in service. As we gain more practical data and case studies from the industry, this fluid application will be used more widely.

References

- [1] D.P. Stockton, J.R. Bland, T. McClanahan, J. Wilson, D.L. Harris and P. McShane, "Natural Ester Transformers Fluids, Safety, Reliability, and Environmental Performance," IEEE Petroleum and Chem. Industry Technical Conf (PCIC) pp 1-7, 2007
- [2] CIGRE Working group A2.35, "New experience in service with new insulating liquids," Brochure No 436, ISBN 978-85873-124-4, 2010
- [3] R. Marin, "Esters – Their structure and Their Properties," CPRI National Conf. on Environmentally Friendly Insulating Liquids (EFIL-2013), New Delhi, pp 1-16, 2013
- [4] IEEE STD C57.147-2006 – IEEE Guide for Acceptance and Maintenance of Insulating Oil in Equipment
- [5] IEEE STD C57.147-2008 – IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers
- [6] Cooper Power Systems, *Bulletin 00092 – Product information – Envirotemp™ FR3™ Fluid – Description*, 2001
- [7] IEC 60296 – Edition 4 – 2012-02, Fluids for Electrotechnical Applications – Unused Mineral Insulating Oils for Transformers and Switchgear
- [8] IEC 62770 – Edition 1.0 – 2013-11, Fluids for Electrotechnical Applications – Unused Natural Esters for Transformers and Similar Electrical Equipment
- [9] ASTM D3487-09 – Standard Specification for Mineral Insulating Oil Used in Electrical Apparatus
- [10] ASTM D6871-17, Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus
- [11] T.A. Prevost, "Dielectric Properties of Natural Esters and Their Influence on Transformer Insulation System Design and Performance – An Update," IEEE PES Transmission and Distribution Conf. Exhibition, pp 30-34, 2006
- [12] S. Zabeschek, "Design of Oil Processing Units for Mineral Oils and Natural Ester Fluids (FR3)," Weidmann Transformer and Technology Seminar, Switzerland, 2014
- [13] Cargill Reference Data R2070 – Envirotemp™ FR3™ Fluid – Dissolved Gas Guide, 2006
- [14] D. Marin, N. Lelekakis and V. Davydov, "Preliminary Results for Dissolved Gas Levels in a Vegetable Oil-filled Power Transformer," IEEE Electrical Insulation Magazine, Vol 26, No 5, pp 41-48, 2010
- [15] Louis Blom, Wilec, *Natural ester oil application in liquid-filled transformers*, EE publisher

