

A Tale of Two Esters - Why the Natural One is the Better Dielectric Fluid

In the quest to replace banned PCB compounds as an alternative liquid insulation for the fire safety of transformers and similar electrical equipment, ester-based dielectric fluids are often the preferred choice because of their environmental benefits and good compatibility with conventional mineral oil.

By Kin Yu LAM, Cargill Bioindustrial, Southeast Asia & Pacific

Despite its commercial introduction more than a decade later than synthetic ester fluid, natural ester, which is largely derived from vegetable seed oil, is by far the market leader now among alternative dielectric fluids, it being used in some 3 million transformers globally [1].

This article reviews and discusses what makes natural ester the insulating liquid of choice over synthetic ester under most conditions.

FIRE SAFETY ASSURANCE FOR NEW AND RETRO-FILLED TRANSFORMERS

As ester-based dielectric fluids were originally developed to replace PCB compounds, it is not surprising that the prevention of pool fire in the event of transformer failure is still widely regarded as the key objective for selecting such fluids over mineral oil. In a recent study conducted by an IEEE task force [2], however, the fire point of one of the commercial synthetic ester fluids was found to be at the borderline 300°C limit for the K-class less flammable liquid and it even dropped below the limit after 424 hours of thermal ageing at 180°C. This raises concerns about its compliance to relevant fire safety regulations.

With a typical fire point above 350°C, meeting the limit for the K-class liquid is never an issue for both unused and in-service natural ester fluids. The high fire point of natural ester also means it is effectively the only option for on-site retro-filling of transformers previously running on mineral oil, since it can tolerate up to about 7% (by weight) of mineral oil contamination without showing a significant drop of its fire point (Figure 1) [3]. For retro-filling with synthetic ester, even for those consistently meeting the K-class liquid standard, the fire point would drop below the required limit at much lower residual mineral oil levels, thereby necessitating a complete oil change under factory environment.

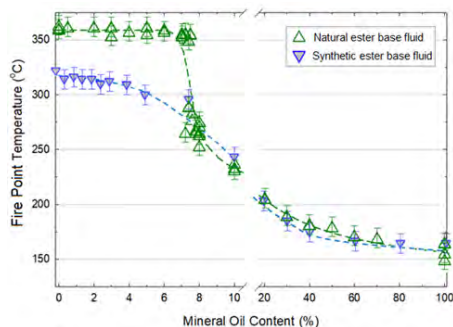


Figure 1 Fire points of natural and synthetic ester fluids at different residual mineral oil contents

ENVIRONMENTAL BENEFITS BEYOND BIODEGRADABILITY

Apart from providing greater assurance of fire safety in new and

retro-filled transformers, natural ester is also preferable over synthetic ester from an environmental perspective. While both esters are readily biodegradable and non-toxic to the environment, only natural ester is derived from plant crops widely available globally and inherently sustainable. That means apart from being more cost effective, the carbon footprint of natural ester is also much lower than synthetic ester. According to the Building for Economic and Environmental Sustainability (BEES) tool developed by the US National Institute of Standards and Technology (NIST), the lifecycle greenhouse gas emission from FR3® Fluid, the most used natural ester fluid derived from soybean oil, is only about 20kg per 1,000 liters, or just 1.8% that of mineral oil, making it effectively a carbon neutral fluid [4].

In contrast, as the raw materials of synthetic ester are mostly derived from petroleum sources, its carbon and environmental footprint is expected to be similar to mineral oil. With the drive toward sustainability and in particular, zero carbon, becoming increasingly a business mandate, natural ester is obviously the preferred choice of fluid for most end users.

EQUIPMENT LIFESPAN AND RELIABILITY

While fire safety and environmental benefits are key issues in the selection of dielectric fluids, perhaps the most important factor that sets natural ester apart from synthetic ester is the former's proven ability to retard the ageing of cellulose paper insulation.

As shown in the IEEE C57.100-1999 sealed tube accelerated ageing tests, the useful lifespan of cellulose paper can be extended by up to 12 times in natural ester as compared to mineral oil [5-6] because of its unique double moisture removal actions through absorption and hydrolysis [7]. This ability to continuously dry the paper insulation in transformers is one of the most important properties of natural ester as a dielectric fluid, as apart from operating temperature, high moisture level is another main cause of cellulose paper degradation.

Continuous removal of moisture not only extends the life expectancy of paper insulation, but it can also help to significantly reduce the risk of dielectric breakdowns as well, as moisture is the main culprit in the reduction of dielectric strength in paper insulation [8] and in the formation of bubbles on the paper surface [9]. Natural ester's outstanding moisture handling properties therefore play an important part in enhancing the reliability of transformers and in reducing the maintenance needed for drying both paper and liquid insulations regularly.

Although synthetic ester is capable of absorbing even more moisture than natural ester due to its higher moisture saturation point, its ability to prolong the lifespan of cellulose paper has never been demonstrated to the same extent, most likely due to the lack of favorable hydrolytic properties in eliminating moisture chemically.

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With the more sterically hindered molecular structure, synthetic ester is generally less susceptible to hydrolysis. This means it is less able to consume the potentially high level of moisture held in the liquid. Even when hydrolysis eventually takes place in synthetic ester, as evidenced in a recent study on the ageing behavior of insulating liquids under high humidity and air exposure [10], the shorter chain fatty acids formed as a result are much more aggressive to the insulation paper. Conversely, in natural ester, the long chain fatty acids formed from hydrolysis are generally non-aggressive and actually help to stabilise the cellulose structure in the paper insulation against degradation [11].

LOADING FLEXIBILITY AND NETWORK OPTIMISATION

Besides the prolonged insulation life that comes with improved reliability as described above, its unique ability in retarding the degradation of cellulose paper also makes natural ester the fluid of choice for increasing the loading capacity of transformers. This opens up the possibility of optimising network utilisation and efficiency.

Based on results obtained from accelerated ageing tests on cellulose insulating papers as described earlier, both the IEC and IEEE standards for high temperature insulation systems [12-13] make provisions for the thermal class of standard and thermally upgraded Kraft papers to be increased by 15°C and 20°C, respectively, with natural ester fluid. As a result, the hot spot temperature limit for natural ester-filled transformers can also be raised proportionately, leading to the possibility of increasing the rated load capacity.

With the feasibility of increasing the nameplate capacity by up to 50% at 95K AWR [14] without the use of costly aramid material, the more compact natural ester-filled transformers can be deployed for applications where space constraint may be an issue, for example, in skid units at solar farms and in towers or nacelles of wind turbines [15].

Increasingly the extra loading capacity provided by natural ester-filled transformers is also becoming the key enabler for driving network optimisation while achieving energy and material sustainability using the so-called sustainable peak loading approach [16]. With the availability of historical loading profile data obtained from smart meters, conventional mineral oil transformers with low average load factor can be identified and replaced by more compacted units running on natural ester fluid. While the extra loading capacity from the smaller natural ester-filled sustainable peak loading transformers can be utilised to cope with the peak loading demand without affecting insulation life, the lower no-load loss of the smaller units can help to improve utilisation and overall energy efficiency for the power grid, as well as significantly reduce the use of non-renewable materials in building the transformers [17].

For synthetic ester-filled transformers, it is not possible to increase the loading capacity in the same way due to its inability to achieve higher thermal class with conventional cellulose papers. To build synthetic ester transformers with increased rated load at higher AWR, solid insulation of higher default thermal class [18], such as the much more expensive Aramid paper, would have to be used, making it much less economically viable.

DIELECTRIC PROPERTIES AND IMPACT OF HARMONICS

As for dielectric properties, both natural and synthetic esters tend to have lower streamer inception voltage than mineral oil under extremely inhomogeneous fields due to their more polar molecular structure. Although this means lower breakdown voltage from ester fluids in impulse tests using highly divergent electrode systems, in practice, it would not be a major issue in the design of internal leads connecting the windings to the bushings and tap changers in power transformers, as it has been shown that there would be no significant difference in the breakdown voltage limits for test electrodes down to 3 mm [19].

On the other hand, the partial discharge inception voltage (PDIV) of natural ester as determined in accordance with IEC TR 61294:1993 is significantly higher than synthetic ester and mineral oil (Figure 2) [20]. The high level of unsaturated fatty acids in natural

ester, which tend to slow down the propagation of discharge within its molecule, is thought to be the main reason for this phenomenon.

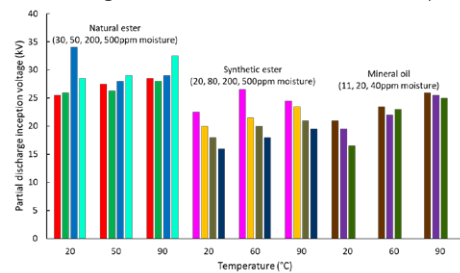


Figure 2 Partial discharge inception voltage of natural ester, synthetic ester and mineral oil as measured according to IEC TR 61294:1993 at different temperatures and moisture levels

Apart from providing greater safety margin for transformers designed to be partial discharge free with mineral oil, the higher PDIV of natural ester also makes it the preferred choice of fluid for transformers connected to renewable energy resources. With its higher PDIV and thermal stability as compared to mineral oil, the use of natural ester fluid has been found to be effective in reducing hydrogen gas generation and sludge formation in transformers exposed to harmonics rich output from solar inverters (results to be published). In addition, a simulation study has also proven that the use of natural ester in place of synthetic ester could help reduce X-wax formation in transformers of high field strength, including those used in wind turbines, again due to its ability to suppress partial discharge activity (Figure 3) [21].

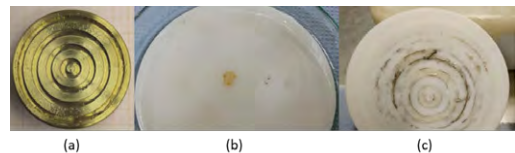


Figure 3 Partial discharge simulating test for X-wax formation. (a) brass electrodes used to represent the winding wires in transformer; (b) trace of ageing product formed after the test with natural ester liquid; (c) X-wax formed after the test with synthetic ester liquid

LOW TEMPERATURE PROPERTIES

While low temperature startup of transformers is not usually considered a major issue in this part of the world, it may still be a concern in some areas under extreme weather condition. Despite the higher pour point of natural ester dielectric fluid as compared to mineral oil and synthetic ester, the general recommendation for energisation under cold conditions as described in clause 4.4.4 of IEEE C57.93-2019 [22] would be considered sufficient. Unlike mineral oil, the existence of free water is not a main concern at low temperatures for both natural and synthetic esters.

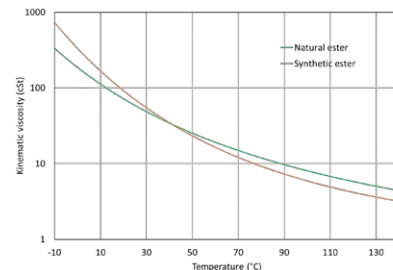


Figure 4 Kinematic viscosity of natural ester and synthetic ester

From the perspective of cold starting, the main benefit of synthetic ester is its low tendency to form crystals at low temperatures, which is particularly advantageous for power transformers equipped with devices like Buchholz relay that come with fluid conservators. However, at temperatures above pour point, the viscosity of synthetic ester is significantly higher than that of natural ester (Figure 4), which may reduce the fluid flow inside the cooling ducts of the windings, leading to poorer heat transfer and cooling efficiency.

THE REAL ISSUE OF OXIDATION STABILITY

Although some users may still consider oxidation stability to be a concern for natural ester, much of this misinformation has been corrected by extensive studies and field experiences [23].

While natural ester is by nature more susceptible to oxidation than synthetic ester and mineral oil because it is mostly made of unsaturated fatty acids, with advanced refining and formulating technologies it is capable of operating in free breathing transformers for many years without exceeding the critical control limits for in-service insulating liquids. Even in the unfavorable situation where impregnated parts are left exposed to air without submerging in the fluid, it would still take more than two weeks under hot and humid conditions for a well formulated natural ester fluid to show any sign of thin film oxidation, thereby making it feasible to carry out most routine maintenance and repair work on transformers without much concern and inconvenience [24]. In a recent study aimed at evaluating the ageing characteristics of different types of dielectric fluids under open air conditions, most of the critical parameters of natural ester associated with fluid oxidation were found to be within the limits for in-service liquids (Table 1) [10]. And even though the breakdown voltage recorded from all the samples subjected to high humidity dropped below the limit for in-service liquids due to the high level of moisture present, those from natural ester were significantly higher than synthetic esters.

Fluid type	Natural ester	Synthetic ester	Limits for in-service liquid/paper [25-26]
<i>High humidity accelerated ageing test under open air (80°C, 80-100% humidity; 4 weeks)</i>			
% Increase in viscosity @40°C	13%	0%	<15%
Breakdown voltage (avg/max) (kV)	20.3/26.5	13.4/14.4	>30
Moisture content (ppm)	1,368	1,696	<400
Total acid number (mgKOH/g)	0.06	0.05	<0.5
Dissipation factor @90°C/50Hz	0.012	0.016	<0.5
<i>High temperature accelerated ageing test under open air (130°C; ambient humidity; 5 weeks)</i>			
% Increase in viscosity @40°C	20%	0%	<15%
Breakdown voltage (avg/max) (kV)	61.1/68.9	57.0/64.4	>30
Moisture content (ppm)	376	94.2	<400
Total acid number (mgKOH/g)	0.25	0.03	<0.5
Dissipation factor @90°C/50Hz	0.056	0.032	<0.5
Retained tensile strength of paper insulation (%)	61.4%	34.0%	>50%

Table 1 Test results on natural ester and synthetic ester dielectric fluids after accelerated ageing tests under open air condition [10]

More importantly, the retained tensile strength of the insulation paper samples immersed in synthetic ester also dropped below one of the end-of-life criteria of 50% after the ageing test at high temperature (Table 1). This clearly demonstrates that the presence of air and moisture would pose an even bigger threat to the paper insulation. With natural ester the paper insulation is in fact much better preserved under such conditions due to its unique paper drying properties as described earlier [5-7].

The overall results, therefore, bring home the point that free breathing conditions are not suitable for all liquid-filled transformers, as the reduction in dielectric strength and increase in paper insulation degradation rate are areas of bigger concern than the oxidation of natural ester. In comparison to synthetic ester, natural ester would enable transformers to better cope with temporary free breathing conditions in the event of a breach in the sealing system before the necessary maintenance work can be carried out.

CONDITION MONITORING CAPABILITY WITH DISSOLVE GAS ANALYSIS

As the most widely used alternative dielectric liquid, a large amount of dissolved gas analysis (DGA) data has been collected for natural ester fluid derived from soybean oil. As shown in Table 2, the 90th percentile thresholds of the combustible gases for soybean oil based natural ester are statistically much more reliable than synthetic ester, as indicated by the much smaller variance (95% confidence level) [27]. DGA results can therefore be analysed and interpreted with much higher confidence level for this type of natural ester fluid.

Ester fluid type	Number of records	H ₂	CH ₄	C ₂ H ₂	C ₂ H ₄	C ₂ H ₆	CO
Soybean natural ester	90 th percentile	112	20	232	18	1	161
	95% confidence level	(105-118)	(19-22)	(219-247)	(17-20)	(1-1)	(150-179)
Synthetic ester	90 th percentile	64	104	124	150	13	1344
	95% confidence level	(52-82)	(89-135)	(105-362)	(79-215)	(0-33)	(937-1526)

Table 2 DGA thresholds of soya bean natural ester and synthetic ester as per the IEEE DGA Guide for ester fluids [27]

WHEN NATURAL IS BETTER THAN SYNTHETIC

While the effort spent on enhancing oxidation stability and low temperature characteristics has enabled synthetic ester to be used in some niche applications, by and large it has also compromised some of the most important properties that come with natural ester, including raw material availability, cost effectiveness and sustainability. With regard to the key aspects of dielectric fluid as summarised in Table 3, one would have to conclude that in the tale of the two esters, the natural one is indeed the better choice over the synthetic one in most applications.

	Natural ester	Synthetic ester
Base fluid type	Vegetable oil	Pentaerythritol ester
Fire point	>350°C	~305-315°C
Biodegradability/toxicity	Best in class	Readily/non-toxic
Biosafe/carbon footprint	Yes/very low	No/similar to mineral oil
Increase of cellulose paper lifespan	Up to x12	Marginal
Increase in thermal class of cellulose paper	15-20°C	No
General dielectric properties	Equivalent to mineral oil	Equivalent to mineral oil
Partial discharge inception voltage	Higher than mineral oil	Lower than mineral oil
Crystallization at -25°C	Yes	No
Viscosity at -10°C	~330cSt	~730cSt
Fluid oxidation stability	Adequate	Good
DGA Diagnostic capability	Robust	Limited

Table 3 Comparison of key properties of natural and synthetic esters

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