

VEGETABLE OILS AS SUBSTITUTE FOR MINERAL INSULATING OILS IN MEDIUM-VOLTAGE EQUIPMENTS

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INTRODUCTION

Mineral oils are the most widely used fluids for electrical insulation and heat transfer in equipment such as transformers, capacitors, bushings etc. Their technical characteristics have been optimised during the last century to fit the requirements of these application fields. Nevertheless, even if mineral oils still represent an excellent technical vs. cost solution, their environmental performance has to be addressed.

In the frame of the sustainable development principles, the search for “green products” as an alternative to mineral oils has to be carried out. Because of its non fossil origin, vegetable oil could be an appropriated response to environmental, safety and health problems, and could reduce the exploitation and end-life costs of transformers.

Some vegetable oils meet the technical requirements of conventional dielectric liquids. Their high biodegradability and non toxicity are other qualities making these natural oils interesting raw materials for the development of new environmental friendly dielectric fluids.

About Vegetable Oils

Vegetable oil basically consists of triglycerids, naturally synthesized by esterification of the tri-alcohol, called glycerol, with three fatty acids.

The fatty acids are composed of linear hydrocarbon chains ended by a carboxylic function. These molecules have an even number of carbon atoms (typically from 8 to 22 in triglycerids) and the chain can be saturated or mainly mono-, di- and tri-unsaturated. Stearic acid is an example of a saturated fatty acid. Its raw formula is $\text{HOOC}-(\text{CH}_2)_{16}-\text{CH}_3$ and it is symbolized by the expression C18:0, where the two numbers correspond to the numbers of carbon atoms and unsaturated bound(s) in the molecule, respectively.

The different crop plants lead to seed oils which can be characterized by the relative quantities of fatty acids as shown in Table I. The nature of the fatty acid components of triglycerides plays an important role in determining the physico-chemical properties of bio-oil.

Table I : Typical Fatty Acid Profiles (%) of 3 Classical Seeds

Fatty acids	Castor-oil	Rapeseed	Sunflower
C16:0	0.95	4.29	5.77
C18:0	1.00	1.57	3.97
C18:1	2.29	55.7	27.2
C18:1(OH)*	90.0	0.00	0.00
C18:2	3.48	19.3	59.2
C18:3	0.35	10.2	0.23
C20:0	0.00	0.47	0.24
C20:1	0.22	1.20	0.13
C22:0	0.00	0.64	1.44
C22:1	0.00	0.23	0.00
Other	1.71	6.40	1.82

* mono-hydroxylated oleic acid

Many other compounds, in small amount, give their consistency, colour and odour to the vegetable oils. Refining processes can specifically eliminate these molecules, depending on the desired properties.

INVESTIGATIONS

In order to select the best raw material for electro-technical applications, we measured the main properties of several seed oils and compared them with the IEC standards requirements for insulating mineral oils [1] and synthetic organic esters [2]. As no specific international standards exist for vegetable oils yet, the applicability of these two specifications was assumed.

Some candidate oils contain a high percentage of unsaturated fatty acids, resulting in lower viscosity and better low-temperature properties. Others have a higher percentage of saturated acids, known to improve oxidative stability. An optimal balance has to be selected between the two types of fatty acids contents in seed oils.

Looking at dielectric formulations exclusively based on biodegradable and non-toxic vegetable products, we have also tested some chemical derivatives of these seed oils. Mono-esters were prepared from refined oils with different alcohols, such as methanol, *iso*-propanol etc. The reaction separates the fatty acids associated into each triglycerid and creates three single esters. This could help to improve the rheology of the oil.

The key parameters and the corresponding measuring methods which have been considered first are :

- Breakdown voltage IEC 60156
- Pour point ISO 3016
- Viscosity (at 40°C) ISO 3104

The breakdown voltage at power frequency is obviously of prime importance with respect to the insulation ability of a liquid.

The pour point is the lowest temperature at which the oil flows. To avoid local over-heating in cold start operations, it is recommended that the pour point should be 10 K below the IEC Lowest Cold Start Energizing Temperature (LCSET), which is standardized at -30°C . The corresponding referring pour point is consequently -40°C .

The insulating oil viscosity is also an important parameter to describe heat dissipation in the transformer. At operating temperatures, the thinner the oil, the easier it flows. This characteristic becomes important when considering non-forced circulation transformers.

RESULTS

Breakdown Voltage

Untreated seed oils and their esters show breakdown voltage values up to 70 kV and thus fulfilling both IEC requirements for mineral oils and synthetic esters (cf. Table II).

The power frequency breakdown voltage of an insulating liquid is primarily sensitive to its water content. The samples we have tested had absolute water content between 150 and 200 ppm. Such values are high if compared with typical values for unused mineral oils and similar to what is observed for synthetic esters. Vegetable oils and esters, because of their chemical structure, have larger saturation limits than mineral oils. It has been shown that the effect of water depends on the relative moistness of the liquid [3]. So, an adequate comparison has to refer to relative humidities. At room temperature, the water saturation limit of vegetable oils is about 750 ppm, and 40 ppm for mineral oils ; an absolute moisture of 200 ppm in a vegetable oil reported to its saturation limit leads to a relative humidity (RH) of 26.7 %. This RH value is equivalent to an absolute water content of 10 ppm in mineral oil, which is commonly measured after a dehydration treatment. Accordingly, the measured dielectric strength of vegetable oils and esters can be consistently compared with the value specified for treated mineral oils. This result confirms the actual high dielectric strength of these vegetable products.

Viscosity and Pour Point

The measurements (see Table II) show that pour point and viscosity values of unprocessed seed oils exceed the specified values.

After esterification, the viscosity of the oils passes below the specified $35 \text{ mm}^2.\text{s}^{-1}$ value for synthetic organic esters. The measured value tends towards $12 \text{ mm}^2.\text{s}^{-1}$ *i.e.* the specified value for mineral oils. This is consistent with the fact that esterification corresponds to the separation of big triglycerids into smaller molecules that flow more easily, improving the oil rheology.

The pour point is less affected by the modification of the molecular structure of the fluid, but it can be noticed that the bigger the alcohol, the lower the pour point. The fatty acid esters, originated from particular alcohol (referred as X-ol in the Table II below) reaction, present a pour point very close to the referring mineral oil limit.

Table II : Measured Properties for three Seed Oils and some of their Esters

	Breakdown voltage, kV	Pour point, °C	Viscosity @ 40°C, $\text{mm}^2.\text{s}^{-1}$
IEC Limit value	> 70 (1)	< -40 (2)	< 12 (3)
<u>Castor Oil</u>	86.7 ($\pm 3.1\%$)	-27	261.5
Methylic esters	74.1 ($\pm 5.9\%$)	-22	14.4
<i>iso</i> -Propylic esters	96.0 ($\pm 5.2\%$)	-35	16.0
X-olic esters	70.0 ($\pm 13.6\%$)	< -38	11.0
<u>Sunflower Oil</u>	58.4 ($\pm 5.1\%$)	-15	41.2
Methylic esters	79.6 ($\pm 8.2\%$)	-8	11.1
<i>iso</i> -Propylic esters	82.9 ($\pm 6.9\%$)	-22	12.0
<u>Rapeseed Oil</u>	97.1 ($\pm 3.7\%$)	-23	41.1
Methylic esters	67.4 ($\pm 7.8\%$)	-16	7.2
<i>iso</i> -Propylic esters	85.0 ($\pm 9.8\%$)	-24	5.2
X-olic estrers	89.5 ($\pm 4.9\%$)	< -38	8.1

(1) After laboratory treatment (sintered glass filtration at 60°C by vacuum) ; > 45 kV for untreated synthetic esters

(2) Standard LCSET–10K

(3) < $35 \text{ mm}^2.\text{s}^{-1}$ for synthetic esters for transformers

DISCUSSION

The present work allows the selection of the most satisfying seed species and oil derivatives to use for an electrical transformer application. Accordingly, the most promising candidates are based on refined rapeseed oil and its derived esters. A prototype composition, without any additives, has been patented and work is in progress to achieve a more complete characterization and validation of such formulae. The investigations are carried on in collaboration with transformer manufacturers, seed producers and oleochemist partners.

The preliminary results definitely demonstrate the ability of these alternative liquids to fulfil the key characteristics for use in transformers. In particular, all the requirements for unused synthetic organic esters are fulfilled by these first formulations. A summary of the results is shown in Table III regarding the properties of existing dielectric liquids.

Table III : Comparison of Transformer Dielectric Fluids – Typical Values

	Mineral Oils	Silicone Oils	Synthetic Esters	Vegetable Oils	Test Method
Dielectric Breakdown, kV	30 / 85	35 / 60	45 / 70	82 / 99	IEC 60156
Relative Permittivity at 25°C	2.1 / 2.5	2.6 / 2.9	3.0 / 3.5	2.7 / 3.0	IEC 60247
Viscosity at 0°C, mm ² .s ⁻¹	< 76	81 / 92	26 / 50	143 / 77	ISO 3104
“ at 40°C, “	3 / 16	35 / 40	14 / 29	15 / 37	
“ at 100°C, “	2 / 2.5	15 / 17	4 / 6	4 / 8	
Pour Point, °C	-30 / -60	-50 / -60	-40 / -50	-19 / -33	ISO 3016
Flash Point, °C	100 / 170	300 / 310	250 / 270	315 / 328	ISO 2592
Fire Point, °C	110 / 185	340 / 350	300 / 310	350 / 360	(1)
Density at 20°C, kg.dm ³	0.83 / 0.89	0.96 / 1.10	0.90 / 1.00	0.87 / 0.92	ISO 3675
Specific Heat, J.g ⁻¹ .K ⁻¹	1.6 / 2.0	1.5	1.8 / 2.3	1.5 / 2.1	ASTM E1269
Thermal Conductivity, W.m ⁻¹ .K ⁻¹	0.11 / 0.16	0.15	0.15	0.16 / 0.17	(DCS)
Expansion Coefficient, 10 ⁻⁴ .K ⁻¹	7 / 9	10	6.5 / 10	5.5 / 5.9	ASTM D1903

(1) Cleveland open cup procedure

Thermal Performance and Fire Safety

Regarding the characteristics for mineral oils and other dielectric liquids, the thermal properties of vegetable oils appear as equivalent, or better.

Thanks to a better caloric transfer vs. slower circulation, it can be estimated that the thermal conductivity and specific heat could compensate for the slightly too high pour point and low-temperature viscosity.

The comparison between coefficients of volume expansion shows that the vegetable oil one is the lowest. This characteristic means that the designed tanks of conventional transformers can be used trouble free when filled with such liquids.

In addition, test data show that the vegetable oil and ester based fluid has the highest ignition resistance. The flash point and fire point are above those of less-flammable dielectric fluids currently available.

So, natural vegetable fluids appear as an interesting new non-flammable liquids, that could answer to the banning of PCBs and other halogenated dielectrics fluids used in liquid-filled fire resistant transformers.

About Oxidation Stability and Biodegradability

Most obviously, edible seed oils and food grade products cannot be as stable as petroleum-based oils and other non-biodegradable dielectric fluids. Oxidation and hydrolysis are the main ageing mechanisms. To make vegetable formulated oil more stable, oxidation inhibitors and metal passivators (presence of copper and iron are known to enhance the degradation process) will probably be added to the basic fluid. Such additives will have to be exclusively selected among food grade materials. But, small-scale accelerated aging tests already demonstrate the good behaviour of some of the selected products (data to be publish).

Another mean to improve the life duration of vegetable oil is to avoid applications with continuous air exposure such as in free breathing equipment. With this consideration, the technology of the liquid full-filled transformers with hermetically sealed tank, typically used by EDF company as distribution transformers, seems to be well suited to these liquids.

Since such equipment are spread everywhere in the environment, improved management of the risks of water and soil pollution by dielectric leakage should consider biodegradable oil as particularly interesting.

More detailed tests should help define the combination and quantities of additives to optimise the biodegradability versus oxidation stability balance for each different application.

Environmental and Health Issues

Today, not only technical performances and value are key criteria in material selection, but also overall environmental and total life-cycle costs are entering the analysis. The minimum health and environmental related requirements for applying a liquid as a dielectric fluid are listed below :

- Non-toxicity,
- Biodegradability,
- Production of only acceptable and low-risk thermal degradation by-products,
- To be recyclable and readily disposable,

The alternative non-petroleum liquid presented here meets all these criteria, with the additional advantage to derive from renewable resources, unlike mineral oils. Moreover, the selected agricultural plants on which this edible seed-oil is based are widely available established crops.

Other considerations

According to the chemical structure of natural triglycerids and esters, the compatibility of vegetable oils with standard transformer insulating materials and components should not cause any problem. This point, within other matters, has to be clarified with real experimentation on transformers filled with vegetable oil. The objective is to confirm that no design modification of transformers is necessary.

It is obvious that any change will have consequences on the price of the apparatus even if it seems already acquired that the price of vegetable oil formulations can compete with conventional mineral oils and fire resistant liquids ones.

The *in situ* long-term assessment of properties and behaviour of vegetable oil-filled transformers is the future required step to definitely validate the fluid and its use. This stage will allow defining the preventative maintenance tests and operations to follow.

Meanwhile, the formal recognition from the code of less-flammable liquid filled transformers will also have to be achieved to complete the validation of the vegetable esters based dielectric liquid.

CONCLUSION

Nowadays, it is increasingly important that dielectric fluids provide a better balance between high functional performances *versus* low environmental impacts. Inside transformers, a stable, chemically inert fluid having good thermal and dielectric properties is needed. Outside (for instance in the event of release), the fluid should become environmentally benign by being non-toxic and readily biodegradable.

In this frame, the agricultural commodity oils, used mainly in food products, are not only widely

available, but, unlike mineral oil, are derived from renewable resources. They are biodegradable and do not contribute significantly to the net greenhouse gases released to the atmosphere.

The inherent environmental performance, fire safety and chemical and electrical properties of natural vegetable oil and ester based dielectric coolants are advantageous. The insulating and coolant liquid presented in this paper, specifically formulated from conventional crop plants products for use in tank sealed distribution transformers, offers an interesting alternative to mineral oil-filled transformers, but also to dry and non-flammable liquid-filled types used in specialty applications.

REFERENCES

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