

Investigations on Eco Friendly Insulating Fluids from Rapeseed and Pongamia Pinnata Oils for Power Transformer Applications

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Abstract – Transformer mineral oil which is normally hydrocarbon based is non- biodegradable and pollutes the environment in all aspects. Though vegetable oils are eco-friendly in nature and potentially could be used in transformers as a replacement for the mineral oil, there usage is restricted because of their oxidative instability. The present work focuses on using rapeseed oil and pongamia (pongamia pinnata) oil as effective alternatives for the traditional mineral oil in power transformer. The oxidative stability of the rapeseed oil and pongamia oil is increased by using combinations of the natural and synthetic anti-oxidants as additives. The parameters like breakdown voltage, viscosity, flash point, fire point are measured for the rapeseed oil and pongamia oil with and without the additives as per IEC and ASTM standards. The results shown encouraging changes in the parameter values and ensures the use of the oils as a potential alternative insulation in power transformers.

Keywords: Anti-oxidants, Eco-friendly oil, Oxidative stability, Power transformers.

1. Introduction

The Polychloro biphenyl (PCB) was used as a non-flammable insulating fluid in transformers since 1932[1] and until 1979. PCB a highly toxic material and is classified as persistent organic pollutant. Hence PCB productions were banned by the United States Congress in 1979 and by the Stockholm Convention on Persistent Organic Pollutants in 2001[2]. Later in 1978 as an alternative for the PCB, Isopropyl biphenyl was used as the dielectric insulating fluid in the power transformers [3]. In addition, silicone fluids like polydimethyl siloxane (PDMS) and high temperature hydro carbons (HTH) were also used [4, 5]. Though their insulating property was found to be excellent both of them are flammable liquids with high fire point. Synthetic liquids like Ester, Perchloro ethylene are also used, as they have good dielectric strength and heat transfer characteristics, their high cost notwithstanding. Crude oil based mineral oil are refined in such a way as to get the desirable property of insulation. The transformer mineral oil is non-biodegradable, besides heavily polluting land and water. Several billion litres of transformer oils are being used worldwide in the power transformers as insulating and cooling medium [6]. Nowadays, the faster exploitation of petroleum products makes it necessary to conserve and reduce its usage. Considering the environmental pollution it creates the need for alternative sources for replacement of the transformer

mineral oils. Vegetable oils are the alternative sources which come in handy and are available in plenty. The usage of vegetable oils for power capacitors was suggested in 1990s [7, 8]. The vegetable oils like coconut oil, sunflower oil were used in transformers [9, 10]. The vegetable oils are being used in transformers and they satisfy the industry standards with regard to performance and other aspects [11].

Though we have advantages in using the vegetable oils, there are some disadvantages too like high viscosity and poor oxidative stability [12]. As the vegetable oils are lacking in oxidative stability, they are used less in the industries. The natural ester's [Vegetable oil] oxidation stability and performance depends on the composition of the fatty acids. The decrease in the oxidative stability and the shelf life of the oil is due to the removal of antioxidants [13].The antioxidants are the chemical compounds which forbid the oxidation process due to oxygen. Its function is to interrupt the propagation of the free radical chain. The popular antioxidants are hydroxyl phenol compounds. Some of the phenolic antioxidants include Butylated Hydroxyanisole (BHA), Butylated Hydroxytoluene (BHT), Propyl Gallate (PG) and the natural antioxidants ascorbic acids, α – tocopherole and these were selected after careful study. Raymon et al., performed various analyses in natural oils like sunflower, soya bean, rice bran, corn oil [14] and in this work the rapeseed oil and pongamia oil in combination with and without additives were selected and studied their insulating properties.

2. Additives

The antioxidants and synergists are used as the additives

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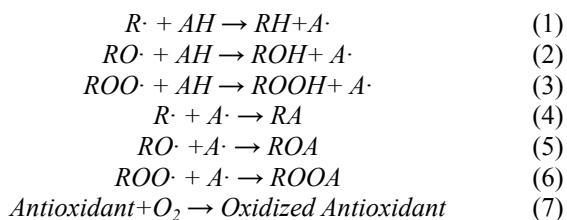
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and catalysts respectively for improvement of the oxidation stability.

2.1 Antioxidant

An antioxidant is a chemical substance that forbids the attack of oxygen which is the oxidation process [15]. The antioxidants interrupt the oxidation process by reacting with fat radical to form a stable radical; this does not react with oxygen. In food industry it is called food additive which increases the shelf life of foods by protecting them against deterioration due to oxidation. Antioxidants decrease the action of formation of free alkyl radicals and thereby interrupting the dispersion of free radical chain. It also acts as hydrogen donor which helps in reducing the dispersion of free radical chain. The general form of the reaction is shown as



- R· - Alkyl radical of fatty acid
- AH - Antioxidant
- RH, ROH, ROOH - Fatty acid
- A· - Antioxidant radical
- RO· - Alkoxy radical
- ROO· - Peroxy radical

The alkyl radical (R·), alkoxy radical (RO·), peroxy radical (ROO·) of fatty acid reacts with the antioxidant (AH) and gives the fatty acid RH, ROH, ROOH and antioxidant radical (A·)(Eq. 1,2,3). The alkyl radical, alkoxy radical and peroxy radical with antioxidant radical reacts and gives a non-radical product such as RA, ROA and ROOA (Eq. 4, 5, 6). In the process of neutralizing the free radicals, the antioxidants become oxidized, thereby increasing the process of oxidation (Eq. 7). Hence, there is a constant need of filling of antioxidant sources [16].

The most popular antioxidants are hydroxyphenol compounds. They have low activation energies for hydrogen donation process. The antioxidant free radicals do not initiate other free radicals immediately. They react with the lipid free radicals to form stable compounds. It functions as oxygen interceptors in the oxidative process thereby breaking the chain reaction which slows down the oxidation process. Some common phenolic antioxidants are Butylated Hydroxy Anisole (BHA), Butylated Hydroxy Toluene (BHT), Propyl Gallate (PG) and Tertiary Butyl Hydro Quinone (TBHQ). Obviously, they donate hydrogen to the free radicals and form as a complex between a lipid radical and the antioxidant radical because of the loss of the hydrogen. The types of antioxidants are listed in Table 1.

Table 1. Types of Antioxidants

Natural Antioxidant		Synthetic Antioxidant	Synergists
Vitamin-E (TOCO PHEROL)	Vitamin-E (TOCO TRIENOL)	Butylated Hydroxy Anisole	Ascorbic Acid
		Butylated Hydroxy Toluene	Carsonic Acid
Alpha(α)		Tert Butyl Hydro Quinone	Citric Acid
Beta(β)		Propyl Gallate	Phosphoric Acid
Gamma(γ)		Pyrogallol	Ethylene Diamene tetra-acetic acid
Delta(δ)		Lauryl Tert Butyl Hydro Quinone	Carotenes
		2,4,5- Trihydroxy butyropenone	Oryzanol Rosemary Extracts

2.2 Synergists

The important substance used for increase of the oxidation stability is the synergist. Synergists are the chemical substances which used to increase the effectiveness of a primary antioxidant. The copper and iron metallic ions act as pro oxidants which are the catalyst in oxidation process. Synergists are more effective when used along with an antioxidant rather than in isolation. Some of the synergists are citric acid, phosphoric acid, and some of their derivatives. The study shows that citric acid can be used in conjunction with the phenolic acid as a synergist [17, 18].

2.3 Eco-friendly fluids

The rapeseed oil [19, 20] and pongamia oil [21, 22] were used as base fluid for testing. These oils are rich in oleic acid and were selected due to inherent higher stability of high oleic oils over commercial oils [23]. The Table 2 shows the fatty acid composition of oils [24]. The oils were subjected to vacuum chamber and pressure of 50 Pa was maintained upto 48 hours for degasifying to remove the moisture content from it. The various parameters like flash point, fire point, viscosity, breakdown voltage of the base fluids were tested and the results are shown in the Table 2. The base fluid 1 and 2 were mixed with various combinations in the proportions of 2.5 g and 5 g of antioxidants to measure the performance of it. In addition,

Table 2. Composition of fatty acids in oils

	Saturated fatty acid			Unsaturated fatty acid		
	Wt%	Name	Symbol	Wt%	Name	Symbol
Rapeseed oil	4	Palmitic	16:0	56	Oleic	18:1
	2	Stearic	18:0	26	Linoleic	18:2
				10	Linolenic	18:3
Pongamia pinnata oil	11.65	Palmitic	16:0	51.59	Oleic	18:1
	7.50	Stearic	18:0	16.64	Linoleic	18:2

Table 3. Test results of base fluids

Critical Parameters	Base Fluid 1 (Rapeseed)	Base Fluid 2 (Pongamia pinnata)
Breakdown voltage (KV)	32	27
Viscosity(Cst) at 40°C	62	32
Flash Point (°C)	320	240
Fire Point (°C)	340	255

multiple combinations of antioxidants were also used in the ratio of 1:1 with the base oil. The breakdown voltages were measured as per the standard IEC 60156 at ambient temperature. The results of the samples with and without additives were compared and discussed.

3. Sample Preparation

The base oil of required quantity was taken and moisture content was measured using the Karl Fisher iteration method according to ASTM D6304. The moisture content was removed by drying the oil with silica gel pellets in the ratio of 1 g of silica to 100ml of oil with a constant stirring of 500 rpm for 6 hours. The moisture content of oil was less than 10ppm after drying. The antioxidants used as additives were of the purity grades above 99% and for investigation purpose the weight of 2.5 g and 5 g with ratio of 1:1 was chosen. Each antioxidant of 2.5 g and 5 g (1:1) was directly dissolved in 500ml of base oils. As there is no particular standard of temperature for mixing antioxidant with oil, we have maintained the room temperature with an increase up to 40°C. The combinations of them were heated to a temperature of 40°C. Then the mixing of antioxidant and base oil was carried out thoroughly by means of vigorous mechanical agitator like

Table 4. Abbreviation and functions of antioxidants

Chemical name and formula	Abbreviated as	Origin	Application
α -Tocopherol Acetate (C ₃₁ H ₅₂ O ₃)	α -T	Natural	Quenchers of singlet oxygen/Synergist
Citric Acid (anhydrous) (C ₆ H ₈ O ₇)	CA		Singlet oxygen scavengers/Synergist
L-Ascorbic acid (C ₆ H ₈ O ₆)	AA		Oxygen Scavengers / Synergist
Butylated Hydroxy Anisole (C ₁₁ H ₁₆ O ₂)	BHA	Synthetic	Free radical Scavengers
Butylated Hydroxy Toluene (C ₁₅ H ₂₄ O)	BHT		Free radical scavengers
Propyl Gallate (C ₁₀ H ₁₂ O ₅)	PG		Free radical scavengers

ultra sonicator. The additives were dissolved completely in base oils. Around forty samples were prepared according to standards and Table 5 shows the samples prepared with two base fluids and their combinations with antioxidants.

4. Testing of Samples

The samples were prepared with several combinations of antioxidants and synergists according to the standard procedures. The measurements of breakdown voltage, Flash point, Fire point, and viscosity of the prepared samples were carried out with standard test procedure as follows:

4.1 Breakdown voltage

The dielectric breakdown voltage of an insulating liquid is a measure of liquid’s ability to withstand electric stress

Table 5. Samples prepared with Base fluids and the antioxidants

Samples from Base fluid 1		Samples from Base fluid 2	
Samples	Combinations of antioxidants	Samples	Combinations of antioxidants
S1	Base fluid 1 + 5 gm α -T	S21	Base fluid 2 + 5 gm α -T
S2	Base fluid 1 + 2.5 gm α -T	S22	Base fluid 2 + 2.5 gm α -T
S3	Base fluid 1 + 5 gm AA	S23	Base fluid 2 + 5 gm AA
S4	Base fluid 1 + 2.5 gm AA	S24	Base fluid 2 + 2.5 gm AA
S5	Base fluid 1 + 5 gm CA	S25	Base fluid 2 + 5 gm CA
S6	Base fluid 1 + 2.5 gm CA	S26	Base fluid 2 + 2.5 gm CA
S7	Base fluid 1 + 5 gm BHA	S27	Base fluid 2 + 5 gm BHA
S8	Base fluid 1 + 2.5 gm BHA	S28	Base fluid 2 + 2.5 gm BHA
S9	Base fluid 1 + 5 gm BHT	S29	Base fluid 2 + 5 gm BHT
S10	Base fluid 1 + 2.5 gm BHT	S30	Base fluid 2 + 2.5 gm BHT
S11	Base fluid 1 + 5 gm PG	S31	Base fluid 2 + 5 gm PG
S12	Base fluid 1 + 2.5 gm PG	S32	Base fluid 2 + 2.5 gm PG
S13	Base fluid 1 + 2.5 gm BHA+ 2.5gm BHT	S33	Base fluid 2 + 2.5 gm BHA+ 2.5gm BHT
S14	Base fluid 1 + 1.25 gm BHA+ 1.25 gm BHT	S34	Base fluid 2 + 1.25 gm BHA+ 1.25 gm BHT
S15	Base fluid 1 + 2.5 gm BHT+ 2.5 gm CA	S35	Base fluid 2 + 2.5 gm BHT+ 2.5 gm CA
S16	Base fluid 1 + 1.25 gm BHT+1.25 gm CA	S36	Base fluid 2 + 1.25 gm BHT+1.25 gm CA
S17	Base fluid 1 + 2.5 gm BHT+ 2.5 gm AA	S37	Base fluid 2 + 2.5 gm BHT+ 2.5 gm AA
S18	Base fluid 1 + 1.25 gm BHT+ 1.25 gm AA	S38	Base fluid 2 + 1.25 gm BHT+ 1.25 gm AA
S19	Base fluid 1 + 2.5 gm BHT+2.5 gm α -T	S39	Base fluid 2 + 2.5 gm BHT+2.5 gm α -T
S20	Base fluid 1 + 1.25 gm BHT+1.25 gm α -T	S40	Base fluid 2 + 1.25 gm BHT+1.25 gm α -T

without failure. The dielectric breakdown voltage indicates the presence of contaminating agents such as water, air bubble, dirt, cellulosic fibers, or conducting particles in the liquid. The breakdown voltage was measured as per the standard IEC 60156 with the kit voltage capacity of 60KV. The test was conducted with spherical head electrodes of standard diameter with a gap of 2.5 mm between them. The oil sample of 500ml was filled up to a level of 40mm above the electrodes. After filling of sample, a time period of 5 – 10 minutes was allowed for settling of air bubbles in the container. Then the test voltage was increased at the rate of 2 kV/s. Five consecutive breakdown voltages were measured with a stand time of 3-5 minutes for each measurement in order to make the byproducts disperse. The average of five voltages was taken as the breakdown voltage of the sample [25]. The sample was tested at room temperature.

4.2 Flash point and fire point

The flash point of the sample was measured with Pensky-Martens closed cup tester according to the standard of ASTM D 93. The brass test cup was filled with the sample of 50ml and fitted with a lid. Sample in the container was heated and stirred at specified rates and a test flame was introduced into the cup at regular intervals with the interruption of stirring until a flash that spreads throughout inside the cup was seen for one second. The corresponding temperature measured is the flash point of sample. The temperature at which flash in the sample sustains for more than five seconds after ignition by open flame is the fire point and it is also measured for the sample. The sample was tested at the room temperature.

4.3 Viscosity

The viscosity of sample was measured using the Saybolt Universal viscometer. The oil sample of 60ml was taken in brass cup with the size of orifice according to the standard ASTM D88. The cup was surrounded by constant temperature bath to maintain the sample at constant temperature. After filling the cup, the cap was removed so that the oil would flow into receiving flask and at the same time the timer was started. The time taken for the flow of 60ml was measured and the viscosity of the sample calculated. The sample was tested at room pressure. The viscosity helps in the process of heat convection in the transformers. The smaller the value of viscosity, higher the rate of heat transfer in transformers [26, 27].

5. Results and Discussions

5.1 Breakdown voltage

The breakdown voltage values of samples are tabulated

in Table 6 and these are represented in Figs. 1 - 6. The samples S14 and S19 of base fluid 1 show increase in breakdown voltage by 59% and 63% respectively. The samples S33, S39 of base fluid 2 show increase in breakdown voltage by 88% and 59% respectively. Though it seems that the percentage enhancement in breakdown voltage is more for base fluid 2, the mean value of breakdown voltage is less than that of the base fluid 1. The combination of Butylated Hydroxy Anisole and Butylated Hydroxy Toluene, Butylated Hydroxy Anisole and α -Tocopherol enhances the dielectric strength to a satisfied level. The base fluid treated with antioxidants releases less amount of carbon and this helps in reducing the gas

Table 6. Breakdown voltage of base fluids with antioxidants

Antioxidants	Weight in grams	Base Fluid 1 (Kv)	Base Fluid 2 (Kv)
α – TOCOPHEROL	5	42	36
	2.5	39	35
Ascorbic acid	5	25	26
	2.5	24	25
Citric acid	5	27	28
	2.5	27	29
BHA	5	46	36
	2.5	44	34
BHT	5	48	36
	2.5	45	32
PG	5	32	39
	2.5	30	35
BHA+BHT	2.5+2.5	49	51
	1.25+1.25	51	48
BHT+CA	2.5+2.5	49	35
	1.25+1.25	44	35
BHT+AA	2.5+2.5	43	37
	1.25+1.25	41	35
BHT+ α – T	2.5+2.5	52	43
	1.25+1.25	49	38

Table 7. Viscosity of the base fluids with antioxidants

Antioxidants	Weight in grams	Base Fluid 1 (cSt) at 40°C	Base Fluid 2 (cSt) at 40°C
α – TOCOPHEROL	5	56	28
	2.5	52	25
Ascorbic acid	5	58	27
	2.5	56	24
Citric acid	5	55	26
	2.5	52	25
BHA	5	57	28
	2.5	54	27
BHT	5	58	29
	2.5	54	26
PG	5	56	26
	2.5	52	24
BHA+BHT	2.5+2.5	48	27
	1.25+1.25	42	25
BHT+CA	2.5+2.5	50	26
	1.25+1.25	48	25
BHT+AA	2.5+1.5	52	27
	1.25+1.25	50	25
BHT+ α – T	2.5+2.5	45	27
	1.25+1.25	42	25

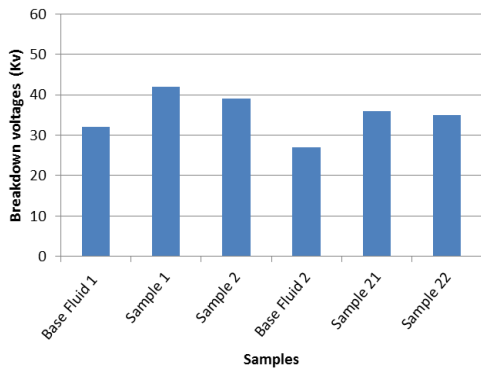


Fig. 1. Breakdown voltage characteristics of base fluid 1 and 2 with α – Tocopherol

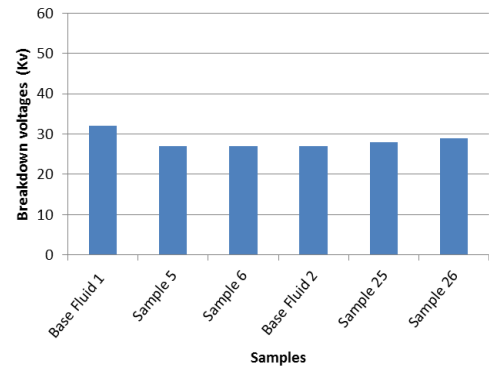


Fig. 4. Breakdown voltage characteristics of base fluid 1 and 2 with Citric acid

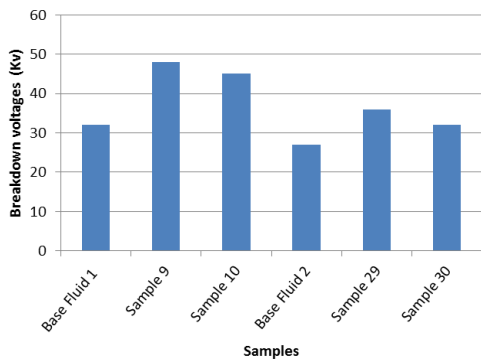


Fig. 2. Breakdown voltage characteristics of base fluid 1 and 2 with Butylated Hydroxy Toluene

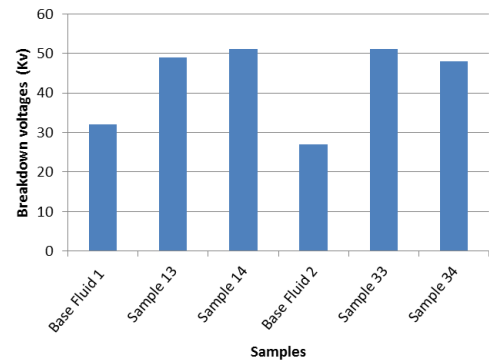


Fig. 5. Breakdown voltage characteristics of base fluid 1 and 2 with Butylated Hydroxy Anisole and Butylated Hydroxy Toluene

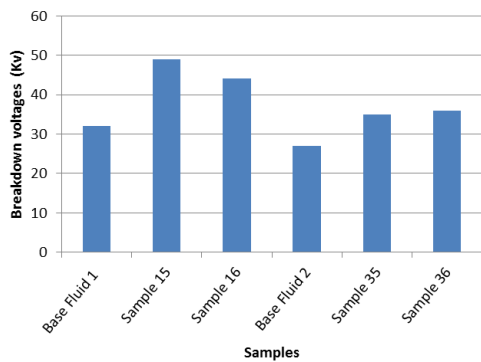


Fig. 3. Breakdown voltage characteristics of base fluid 1 and 2 with Butylated Hydroxy Toluene and Citric acid

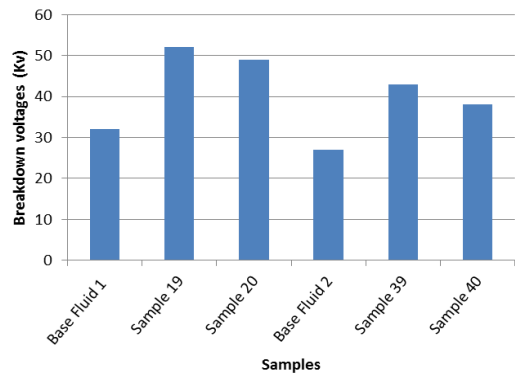


Fig. 6. Breakdown voltage characteristics base fluid 1 and 2 with Butylated Hydroxy Toluene and α – Tocopherol

formation [28].

5.2 Flash and fire points

Antioxidants terminate the formation of chain reaction due to free radicals and reduce the oxidation reactions. The flash and fire point of samples are tabulated in Table 8 and these are represented in the Figs. 7 and 8. The samples 13, 19, 33, 39 prepared with the combination of the Butylated Hydroxy Toluene and α -Tocopherol, Butylated Hydroxy Anisole, and Butylated Hydroxy Toluene with higher concentration have more thermal stability and show a

good enhancement of flash and fire points because of the presence of natural tocopherol and Butylated Hydroxy Anisole. The antioxidant reacts with free radicals and reduces the formation of peroxides thereby reducing oxidation. And also the ability of antioxidant to protect the base fluid depends upon the content of fatty acid of it. The sample prepared with citric acid shows a lesser enhancement of flash and fire points due to the higher rate of ignition mixture formed during the reaction.

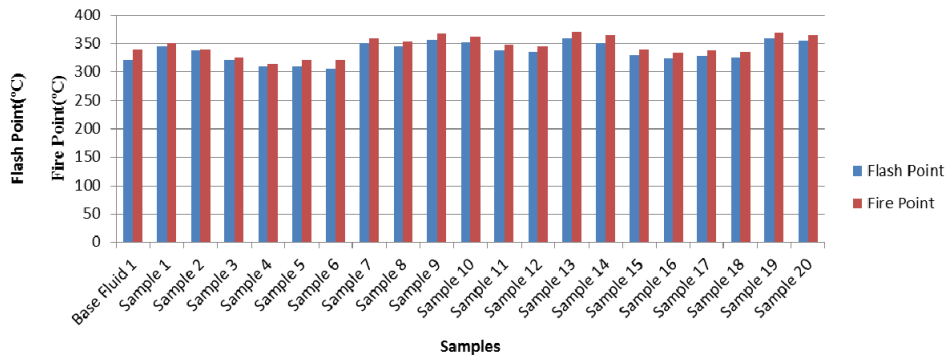


Fig. 7. Flash and Fire point of Base Fluid 1

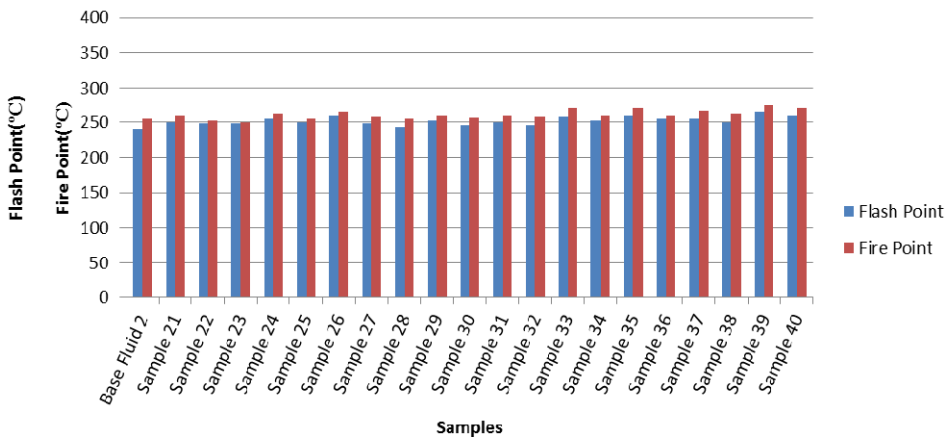


Fig. 8. Flash and Fire point of Base Fluid 2

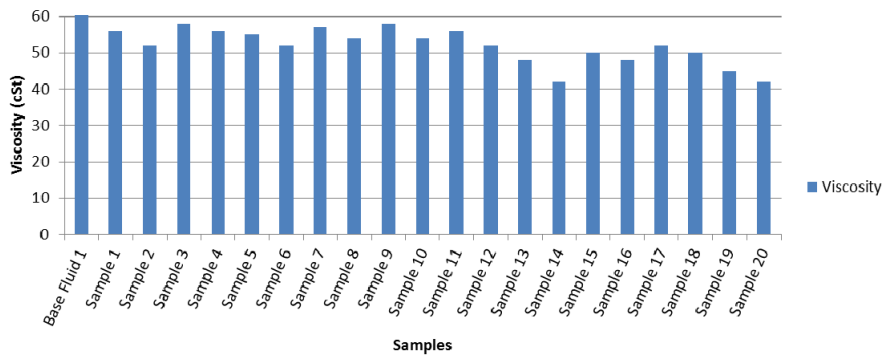


Fig. 9. Viscosity of Base Fluid 1 with additives

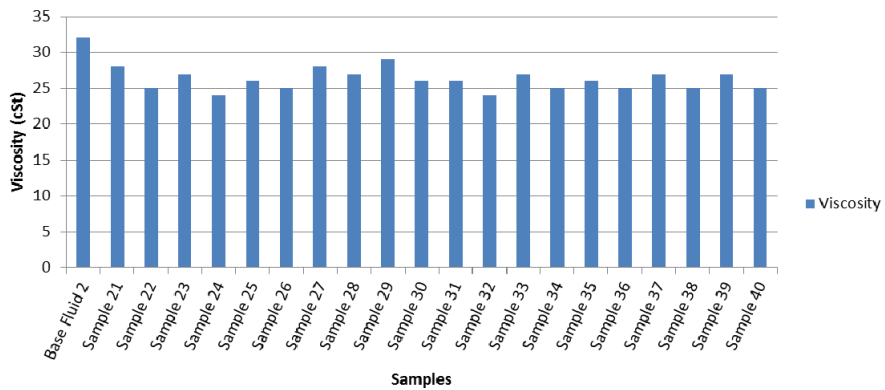


Fig. 10. Viscosity of Base Fluid 2 with additives

Table 8. Flash point and Fire point of the base fluids with antioxidants

Antioxidants	Weight in gms	Base fluid 1		Base fluid 2	
		Flash Point (°C)	Fire Point (°C)	Flash Point (°C)	Fire Point (°C)
α – TOCOPHEROL	5	345	350	235	245
	2.5	338	340	232	242
Ascorbic acid	5	320	325	240	250
	2.5	310	315	234	246
Citric acid	5	310	320	236	246
	2.5	305	320	230	242
BHA	5	350	360	248	258
	2.5	344	354	243	255
BHT	5	357	367	252	260
	2.5	352	362	246	257
PG	5	338	348	250	260
	2.5	335	345	246	258
BHA+BHT	2.5+2.5	360	370	258	270
	1.25+1.25	350	365	252	260
BHT+CA	2.5+2.5	330	340	260	270
	1.25+1.25	324	334	255	260
BHT+AA	2.5+1.5	328	338	256	267
	1.25+1.25	325	335	250	262
BHT+ α – T	2.5+2.5	359	369	265	275
	1.25+1.25	355	365	260	270

5.3 Viscosity

The transformer insulating fluid serves as heat conduction medium irrespective of its dielectric property. The viscosity of fluid is very important in the convection process of heat transfer and temperature is a factor which decides the viscosity. The samples were tested at temperature of 40°C. Even at higher temperature the viscosity value will get reduced but this leads to formation of free radicals which results in sludge formation. The test results of samples are shown in Table 7 and are represented in Figs. 9 and 10. The viscosity is inversely proportional to flow rate. As the viscosity decreases, the flow rate increases thereby enhancing the heat absorption. The samples S14, S20 of base fluid 1 and S24, S32 of base fluid 2 with the combination of antioxidants have shown decrement of viscosity value giving a better scope for high flow rate thereby making them worthy of heat absorption property.

6. Conclusion

The test results show the effective performance of natural esters with the antioxidants. The breakdown voltage and Flash/Fire point of base fluid 1 and 2 have been enhanced with the additives of BHA, BHT, and α-T. The viscosity of test fluids has been decremented by the additives BHT, α-T, and PG. Thus the vegetable oils selected for this study can be used as alternative insulating fluids in transformers.

The transformed natural esters are better alternatives for transformer mineral oil as they offer higher oxidation stability and less formation of gas during reaction. The natural esters are eco-friendly and the aged oil can be easily disposed. The costs of transformed natural esters are more compared with transformer mineral oil. Nevertheless, they are preferable because of their long life and less environmental pollution.

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