

# Features of Eco-Friendly Transformers Using Palm Fatty Acid Ester (PFAE), a New Vegetable-Based Insulation Oil

**Keywords** Transformer, Eco-friendly, Palm fatty acid ester, PFAE, Vegetable oil

## Abstract

In response to a rise of concerns over the global environmental issues and demands for moving away from dependence on fossil fuel for the energy needs, the development of transformers using ester type of insulation oil is in progress. This type of oil is rich in biodegradability and is used to replace conventional mineral insulation oil. We manufacture and sell eco-friendly transformers using Palm Fatty Acid Ester (PFAE) as a vegetable-based insulation oil. The PFAE is a very green and potent high performance oil. Compared with mineral oils, its kinetic viscosity is low (0.6 times) and its dielectric constant is high (1.3 times). When it is applied to oil-immersed transformers, there is therefore a possibility that we can realize a compact design. When it is used as insulation oil, it offers outstanding features in terms of stable supply and oxidation stability. Presently, this type of insulation oil is used for nitrogen-sealed no-voltage tap-changing transformers as well as conservators and Vacuum Interrupter (VI) type on-load tap changers.

## 1 Preface

The amount of annual world electrical insulation oil used is estimated to total 1 million kiloliters. Most insulation oil for transformers is a petroleum-based mineral oil. Recently, environmental challenges such as climate control and global warming have been frequently discussed and there have been pressing challenges for heavy electrical industry to go green (environmentally conscious products) and move away from fossil fuel for energy needs. In this connection, development of ester type insulation oil has become active in the industry because it is rich in biodegradability. Abroad, IEC standardization work for this type oil as a transformer insulation oil is in progress.

Japan AE Power Systems Corporation (a joint venture of Hitachi Ltd., Fuji Electric Co., Ltd., and Meidensha Corporation and it was dissolved in 2012, "AE Power") developed Palm Fatty Acid Ester (PFAE) in 2006 in cooperation with Lion Corporation, a chemical products supplier in Japan. The product

name of Lion Corporation is Pastel NEO. It is being used as a new insulation oil for transformers replacing mineral oil. Since 2009, AE Power launched the sales of PFAE-immersed transformers (Product name: Ecore Trans) using this insulation oil. The concept of this product is that it should not only be green (vegetable-based) but also be even or higher in insulation oil performance than the conventional mineral oil.

After the dissolution of the joint company last year on April 1, 2013, the parties jointly inherited the technologies developed during the period of AE Power. We have continued the development for the PFAE-immersed transformers as environmentally conscious transformers and the production and sales organization remains intact. In regard to the scope of manufacturing, this type of insulation oil is used for nitrogen-sealed no-voltage tap-changing transformers as well as Oil Conservators (OC) and Vacuum Interrupter (VI) type on-load tap changers. This paper introduces the features of the environmentally conscious transformers.

## 2 Features of PFAE Compared with Mineral Oil

**Table 1** shows comparison of physical properties between PFAE and mineral oil. The PFAE offers outstanding features as described below.

- (1) Since this type of oil is derived from a plant as a raw material, there is no exhaustion risk associated with mineral oils. Palm oil assures a high yield per unit area and the amount of annual production stays at a higher rank among vegetable oils. This translates to a stable supply.
- (2) The PFAE is an insulation oil that is 100% chemically stable saturated fatty acid and its acid stability is high compared with mineral oil.
- (3) Dielectric constant is high. With the matching effect of dielectric constant with insulation materials, the concentration of electric field on the oil side can be suppressed. Insulation breakdown voltage can therefore be raised in the composite insulation system.
- (4) Since no sulfur is contained, sulfuric corrosion does not occur.
- (5) Compared with mineral oils, the volume resistivity is low. As such, the phenomenon of fluid charges rarely occurs.
- (6) Compared with mineral oils and conventional vegetable oils, the kinetic viscosity of the PFAE is low. When it is applied to transformers, a higher cooling efficiency can be expected.
- (7) Compared with mineral oils, the flash point is high.
- (8) The PFAE has a nature of biodegradability. Even in the event it leaks into soil, it is soon dissolved into water and carbon dioxide. (Certification for Eco-Mark is acquired in Japan.)

**Table 1** Comparison of Physical Properties between PFAE and Mineral Oils

The PFAE has a low viscosity and offers various outstanding characteristics compared with mineral oils.

Item	PFAE	Mineral oil	Remark (condition)
Density (g/cm <sup>3</sup> )	0.86	0.88	15°C
Kinetic viscosity (mm <sup>2</sup> /s)	5.06	8.13	40°C
Flash point (°C)	186	152	COG
Pour point (°C)	-32.5	-45	
Acid number (mgKOH/g)	0.005	<0.01	
Dielectric constant	2.95	2.2	80°C
Volume resistivity (Ω · cm)	7.1 × 10 <sup>12</sup>	7.6 × 10 <sup>15</sup>	80°C
Dielectric breakdown voltage (kV)	81	70~75	2.5mm

(9) After use, the PFAE can be used again as a biodiesel fuel.

(10) Compared with mineral oils, the abrasion-resistant characteristic of the PFAE is outstanding when sliding between metals is caused in oil. This factor is important for On-Load Tap Changers (OLTC).

(11) Compared with ice (0.917g/cm<sup>3</sup> at 0°C), the density of the PFAE is low. When water content in oil is turned into ice at a low temperature, it does not float up in oil. Since a mobile transformer is equipment whose design always seeks the reduction of mass, the use of low-gravity oil is preferable.

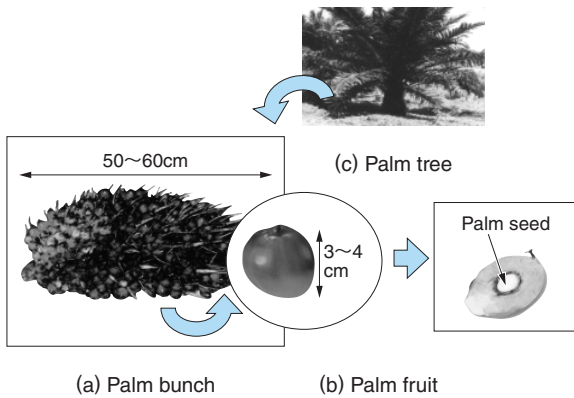
As described above, the PFAE has a variety of outstanding characteristics. When it is applied to transformers, many preferable features can be expected such as an eco-friendly performance, favorable insulation and cooling performance equivalent to, or better than that of mineral oils, and we could also realize the compact transformer design. According to changes in people's consciousness about safety after the East Japan Great Earthquake in 2011, the diffusion of PFAE-immersed transformers is anticipated to increase in consideration of a combination of ideas about energy saving and renewable energy.

Like in the case of mineral oils, we verified that fault diagnosis for transformers using the PFAE as an insulated oil is possible with the use of gas-in-oil analysis.

## 3 Stable Supply

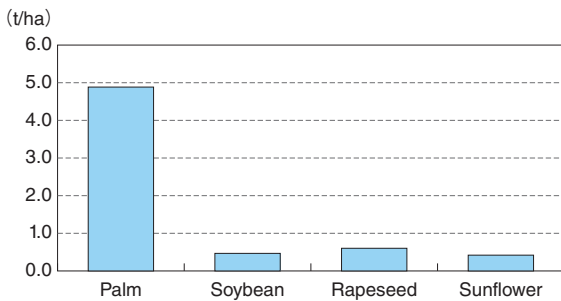
Transformers generally operate for several decades. The stable supply of insulation oil is an essential factor in terms of many years of business continuity, maintenance servicing, and assurance of performance.

**Fig. 1** shows the palm tree (tree and fruit). Palm trees, the raw materials of the PFAE, are cultivated in the Torrid Zone. Their fruits come in a lump called a "bunch" and can be harvested throughout the year. Palm oil can be obtained from palm fruits and palm kernel oil is collected from the seeds. Among vegetable oils, annual yield of palm oil is highest. As shown in **Fig. 2**, the rate of yield per unit area is also highest. Compared with other plants, this figure is far superior to others. Palm oil is used mainly as industrial raw materials for detergents and soap, but in some cases as an edible oil. As the amount of production is increased, consumption rapidly



**Fig. 1 Palm Tree (Tree and Fruit)**

Palm fruits are harvested in a lump called a “bunch.” Palm oil is obtained from palm fruits and palm kernel oil is collected from seeds.



**Fig. 2 Yield per Unit Area Classified for Respective Oil Types**

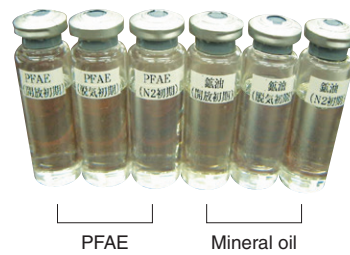
Since this type of oil is derived from a plant as a raw material, there is no concern about depletion unlike mineral oils. The amount of annual production stays at the highest rank among other vegetable oils and the yield per unit area is high, thus assuring a stable supply.

increases as well. In particular, stability is high against oxidation and heating. If it is used as a processing food for frying, deterioration of oil by oxidation can be suppressed. This is a useful advantage by which stability is maintained for a long time. For these reasons, use of this oil is increasingly promoted. In addition, recently application to biodiesel oil has been promoted.

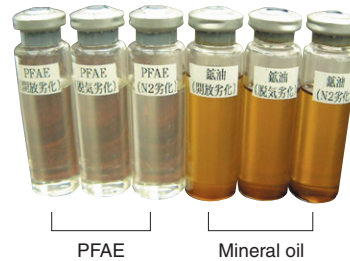
As aforementioned, palm oil is maintaining predominance in international markets in the field of vegetable oils for reasons of high productivity and multiplicity in applications. In addition, its supply is stable.

#### 4 Stability against Oxidation

For mineral oils and the PFAE, we carried out the oxidation stability test stipulated by JISC2101. **Fig. 3** shows the behavior of mineral oil and PFAE



(a) Before test



(b) After test

Insulation oil of 100% chemically stable saturated fatty acid with almost no color change

Color change is perceived due to oxidation and sludge is generated

**Fig. 3 Result of the Oxidation Stability Test (JISC2101: 120°C × 75h)**

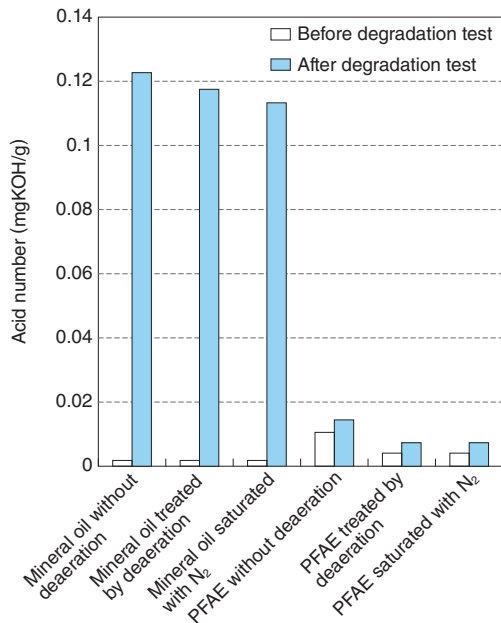
The PFAE remains colorless and transparent and no change is perceived before or after the test under three types of conditions (Open: 300ppm of water content not processed yet, Deaeration: water content reduced to 10ppm by deaeration, N<sub>2</sub>: after water content reduced to 10ppm by deaeration, oil is saturated with nitrogen).

before and after the test, processed under three types of conditions (Open: 300ppm of water content not processed yet, Deaeration: water content reduced to 10ppm by deaeration, N<sub>2</sub>: after water content reduced to 10ppm by deaeration, oil is saturated with nitrogen). Mineral oil shows color changes in all processing conditions, while PFAE remains colorless and transparent and no change is perceived before or after the test.

**Fig. 4** shows the comparison of acid numbers. Compared with mineral oil, the PFAE does not show any change in the acid number before or after the test. Low values are kept throughout the testing. Judging from this result, it is possible to conclude that the PFAE is excellent in terms of oxidation stability.

#### 5 Insulation Characteristics

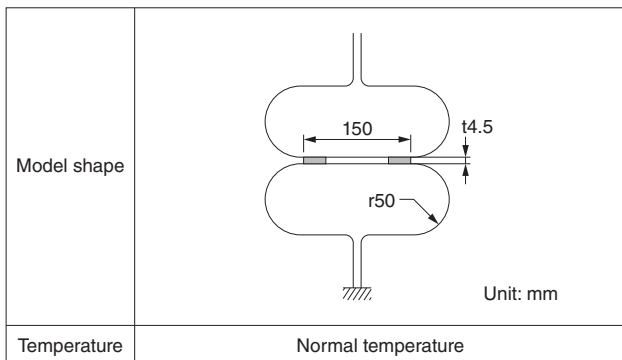
AC and impulse insulation tests were carried out with the use of an inter-section model as a composite insulation model of a transformer. **Fig. 5** shows the model shape between sections. The



**Fig. 4 Comparison of Acid Number**

Compared with mineral oil, the acid number of PFAE does not show any change before or after the test and low values are kept throughout the testing. In conclusion, the PFAE is excellent in terms of oxidation stability.

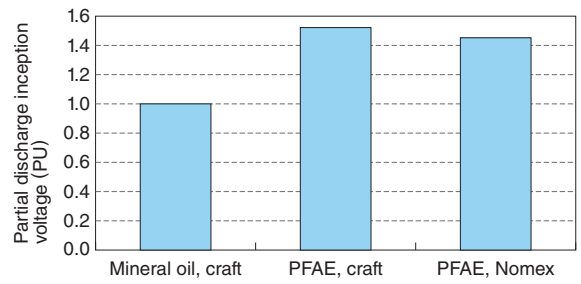
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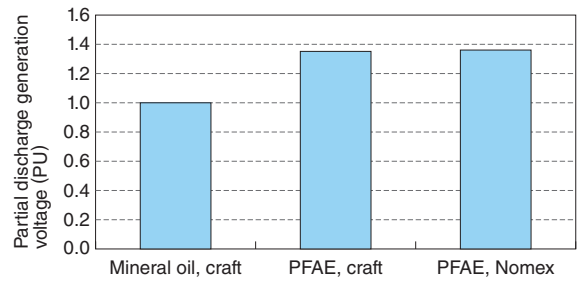
**Fig. 5 Model Shape between Sections**

A flat copper conductor with a cross section of  $3 \times 13$ mm is wound with craft paper of 0.3mm thick. For spacers, high-density pressboards of 4.5mm thick are used.

model wire is a flat copper conductor of  $3 \times 13$ mm, wound by craft insulation paper of 0.3mm in thickness. For spacers, high-density pressboards of 4.5mm thick are used. **Fig. 6** shows the test result. The partial discharge inception voltages of the PFAE against AC and impulse-applied voltages are approximately 1.3 to 1.5 times higher than those of mineral oil. This is considered to be due to the effect of dielectric constant matching between the PFAE and insulation paper. Due to this effect, the concentration of the electric field is relieved around wedge-state oil gaps.



(a) AC voltage



(b) Impulse-applied voltage

**Fig. 6 Partial Discharge Inception Voltages between Sections**

The partial discharge inception voltages of the PFAE against AC- and impulse-applied voltages are approximately 1.3 to 1.5 times higher than those of mineral oil. This is considered to be due to the effect of dielectric constant matching between the PFAE and insulation paper. Due to this effect, concentration of electric field is relieved around wedge-state oil gaps.

In addition, the PFAE offers some more outstanding features regarding insulation which are described below.

- (1) Recently, a new type of problem relating to sulfuric corrosion has been reported. This is a phenomenon in which copper sulfide is deposited on the surface of insulation paper where the temperature is high. The PFAE does not cause such a problem because it does not contain sulfur.
- (2) Compared with mineral oils, the PFAE has a lower volume resistivity. Since electric charges in insulation oil can be easily relieved, the generated surplus charges can easily disappear and fluid charges rarely occur.

## 6 Cooling Characteristics

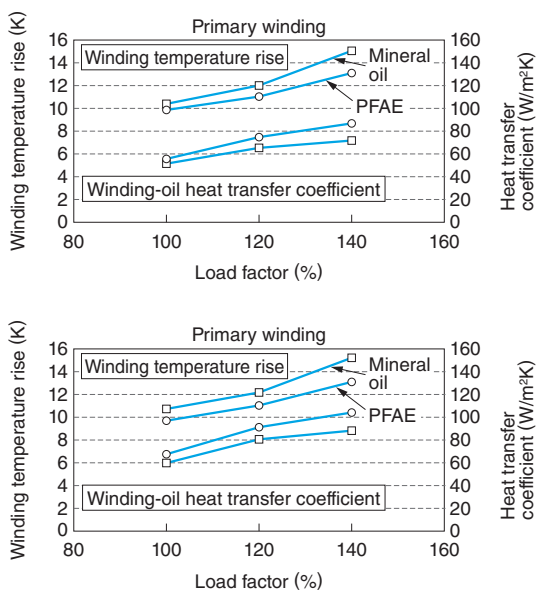
For the confirmation of cooling characteristics of both mineral oil and PFAE, a temperature rise test was carried out in accordance with JEC-2200-1995 with the use of a real transformer specified for 66kV and 2000kVA. **Table 2** shows specifications of the transformer under testing.

The test method used is the secondary winding is short-circuited and loss components are fed

**Table 2** Specifications of the Transformer under Test

In order to confirm cooling characteristics, the temperature rise test has been carried out for both mineral oil and PFAE conforming to JEC-2200-1995.

Applicable standard	JEC-2200
Type and rated frequency	Core type, 50Hz
No. of phases	3
Rated capacity	2000kVA
Rated voltage	66/6.6kV
Cooling system	Oil-immersed self-cooled (ONAN)



**Fig. 7** Winding Temperature Rises and Heat Transfer Coefficients

Compared with mineral oils, the PFAE has a higher winding temperature rise and it shows a lower heat transfer coefficient by approximately 10%. When the load factor is raised, the difference in winding temperature rises between mineral oil and PFAE is increased.

from the primary winding. By changing the load factor (140%, 120%, 100%), winding and oil temperatures are measured. Fig. 7 shows rises in winding temperature and heat transfer coefficients at each load factor. According to the test result, temperature rises in both primary and secondary windings for PFAE are lower than those for mineral oil and the heat transfer coefficient between windings and oil is approximately 10% higher in the case of PFAE. The difference in winding temperature rises between mineral oil and PFAE is increased when the load factor is raised. This phenomenon is due to the characteristics of the kinetic viscosity of both substances.

The PFAE is an insulation oil obtained from

palm oil as a raw material. Palm oil is combined with alcohol in order to obtain low molecular mass compounds and low viscosity. Generally speaking, the flash point tends to decrease as the viscosity is lowered. Since the PFAE is a high-purity substance, a higher viscosity is maintained exceeding the mineral oil, yet the flash point is kept at a higher level compared with mineral oil.

## 7 Biodegradability

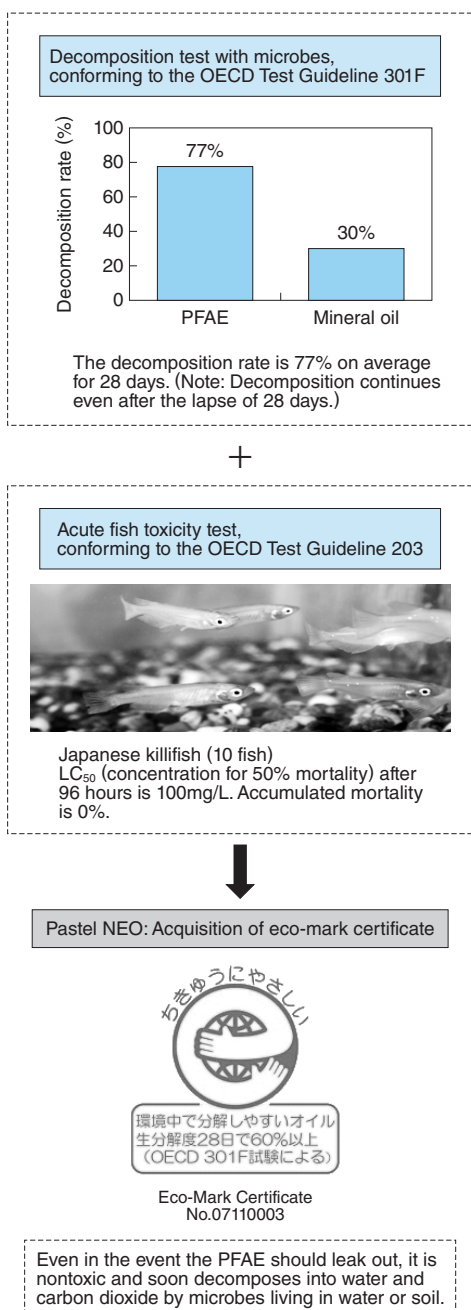
Oil-immersed transformers may cause oil leakage due to the opening of any oil-sealed section (sealed construction at a flange joint part) in the event of a strong earthquake, or as a result of degradation of oil-seal property, or the corrosion of iron plates after many years of operation or under rigorous environmental conditions.

If such leakage oil flows into rivers, lakes, swamps, sea, ponds, dams, or soil, natural and life-line environments and industries, may be damaged. For such damages, the payment of large financial compensations is a possibility. In addition, expenses may be paid for the recovery of the spilled oil. Nowadays, there is a rising international concern for environmental impact. The negative impact by an oil leakage accident will result in a serious problem for the survival of the enterprise which caused such an accident.

On the assumption of a rare but possible occurrence of an oil leakage accident, we performed the biodegradability test in accordance with the OECD Test Guideline 301F (an international safety evaluation and testing method for chemical substances stipulated by the Organisation for Economic Co-operation and Development) and the acute fish toxicity test in accordance with the OECD Test Guideline 203.

According to the result of the biodegradability test, the PFAE shows a high decomposition factor of 77% compared with 30% of mineral oil as shown in Fig. 8. For the acute fish toxicity test, the 96-hour mortality of 10 Japanese killifish (*oryzias latipes*) is 0% at a concentration of 100ppm. This figure satisfies the conditions of 100ppm concentration for 50% mortality.

Based on the results from biodegradability test and acute fish toxicity test, the PFAE have acquired a certificate of eco-mark as shown in Fig. 8. This is a positive factor for the PFAE. Even if the PFAE should leak out, it is nontoxic and soon decomposes



※OECD Test Guideline  
International test method for the safety evaluation of chemical substances determined by Organisation for Economic Co-operation and Development.

**Fig. 8 Certification of Eco-Mark in Japan**

Based on the results from biodegradability test and acute fish toxicity test, the PFAE (Lion Corporation's product name: Pastel NEO) received an eco-mark certification. Even in the event that the PFAE should leak out, it is nontoxic and soon decomposes into carbon dioxide by microbes living in water or soil.

into water and carbon dioxide by microbes living in water or soil.

## 8 Reuse of Waste Oil

For mineral oils, treatment by incineration is the general method used at the time of abandon-

ment. Since the PFAE is a low-viscosity oil derived from plants, it can be reused as a biodiesel fuel. In this way, it can contribute to a low-carbon or recycling-oriented society (see Fig. 9).

## 9 Others

For the OLTC, the abrasion-resistant characteristic is an important factor for the sliding between metals which is caused in the oil. For the PFAE and mineral oil, we carried out the 4-sphere abrasion test (load: 392N, revolutions: 1200min<sup>-1</sup>, testing oil temperature: 75°C, test time: 60 min.) stipulated by the ASTM D4172. According to the result of measuring the abrasion trace diameter of the steel-sphere specimen (4 spheres) performed after the completion of testing, the measured value of the PFAE is smaller than that of mineral oil, suggesting that the abrasion-resistant characteristic of the PFAE is better than that of mineral oil.

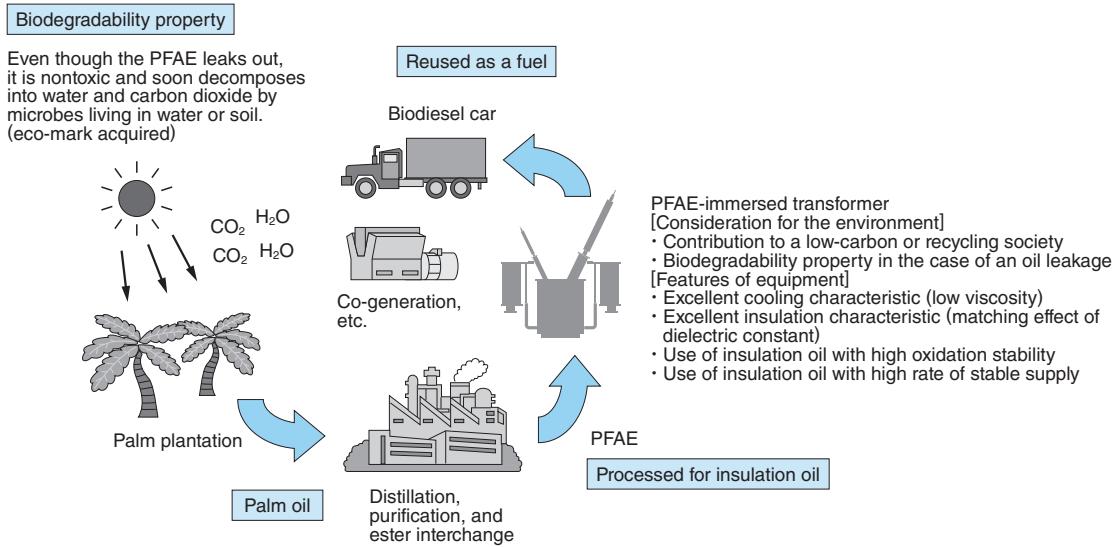
The density of mineral oil is specified by JISC2320 so that it is 0.91g/cm<sup>3</sup> or below at 15°C. This figure reflects its objective that "it is intended to minimize the hazard of ice crystals floating in oil when exposed to a very low temperature." Compared with mineral oils, the PFAE has a lower specific gravity and could fully meet the above requirements. Even for mobile transformers whose design always seeks a lightweight model, the PFAE is a useful substance for its outstanding low specific gravity and cooling characteristics.

## 10 Scope of Commercialization

Presently, our PFAE-immersed transformers are manufactured for a voltage range of 77kV or lower and a capacity range of 30MVA or lower. In an early stage of production, these transformers were manufactured for the nitrogen sealed type with a no-load tap-changer. Now, we meet the requirements of OC and OLTC types.

For the OC type, we investigated the compatibility between a rubber cell and the PFAE. The result indicates that the rubber cell has an equivalent strength as that in mineral oil for both tensile test and bending test. We confirmed that there is no problem in usage. The OC (oil conservator) withstood the durability test of 20,000 actions.

Since the PFAE tends to absorb much water content in the OLTC, we do not use any OC of the breather type. Instead, an expansion chamber is



**Fig. 9 Contribution to a Low-Carbon or Recycling Society**

The PFAE can be reused as a biodiesel fuel. We can expect that it can contribute to a low-carbon or recycling society.

provided atop the tap-changer room and no-pressure sealing device (sealing unit) is installed so that nitrogen is sealed at a no pressure. After the completion of the type test and special tests conforming to JEC-2220-2007, we could confirm that the equipment is free from any problems.

At the time of commercial release, materials used for transformer core-and-coil assembly were checked for their compatibility with the PFAE in order to confirm their adequacy of whether they can be adopted correctly. In particular, utmost care was paid to the use of resin-based materials such as adhesives and painting materials. We spent a lot of time and labor for the confirmation of compatibility.

## 11 Postscript

We manufacture and sell eco-friendly low-viscosity PFAE-immersed transformers with many outstanding features compared with mineral oils. Transformers specified for a voltage range of 77kV or lower and a capacity range of 30MVA or smaller are available. In addition to the nitrogen sealed type with no-load tap-changers, the OC type and the OLTC type are also currently available.

We will continue to promote market penetration and business development so that we can widely contribute to society.

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